OPTICAL MINERALOGY

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THIN-SECTION MINERALOGY

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TABLE OF ABBREVIATIONS

SYMBOLS FOR INDICES OF REFRACTION IN GENERAL USE

Mineral type to which index symbol applies	Symbols used in this text	Symbols used by Dana, Johannsen, Larsen, and Berman	Symbols used by Winchell
Isotropic	n	n	N
Uniaxial			
Extraordinary ray	n_ϵ	ϵ	Ne
Ordinary ray	n_ω	ω	No
Biaxial			
Least value	n_α	α	Np
Intermediate value	n_β	β	Nm
Greatest value	n_γ	γ	Ng

n = index of refraction.

n_α(alpha) = the index of the fast ray in biaxial minerals. The least index of refraction.

n_β(beta) = the index of the ray at right angles to n_α and n_γ.

n_γ(gamma) = the index of the slow ray in biaxial minerals. The greatest index of refraction.

n_ϵ(epsilon) = the maximum (in positive) and the minimum (in negative) index of refraction of the extraordinary ray in uniaxial minerals.

n_ω(omega) = the index of refraction of the ordinary ray in uniaxial minerals. If $n_\omega < n_\epsilon$, the mineral is positive. If $n_\omega > n_\epsilon$, the mineral is negative. n_ω is constant in a given uniaxial mineral, whereas the index of the extraordinary ray varies from n_ω to n_ϵ.

n_1 and n_2 = the lesser and greater indices of refraction of the two rays in any crystal section at random orientation.

X = the axis of greatest ease of vibration. Light vibrating parallel to X travels with maximum velocity (also indicated by α).

Z = the axis of least ease of vibration. Light vibrating parallel to Z travels with minimum velocity (also indicated by γ).

Y = the intermediate axis at right angles to the plane of X and Z (also indicated by β).

ϵ = the axis of vibration of the extraordinary ray.
ω = the axis of vibration of the ordinary ray in a plane at right angles to ϵ.
r = the dispersion for red.
v = the dispersion for violet.
2V = the axial angle within the mineral.
2E = the axial angle observed in air.
Bx_a = acute bisectrix.
Bx_o = obtuse bisectrix.
Ax. pl. = the plane of the optic axes.
μ = micron, thousandth of a millimeter (0.001 mm.).
$m\mu$ = millimicron, millionth of a millimeter (0.000001 mm.).
AU = angstrom unit, tenth of a millimicron (0.0000001 mm.).
Δ = retardation in $m\mu$ (millimicrons).
t = thickness of a thin section. Usually given in hundredths of a millimeter (0.01 mm.).
a, b, and c = the crystallographic axes.
$\measuredangle \alpha, \beta, \gamma$ = angles between the crystallographic axes.
$(n_\gamma - n_\alpha)$ = double refraction for biaxial minerals.
$(n_\omega - n_\epsilon)$; $(n_\epsilon - n_\omega)$ = double refraction for uniaxial minerals.
H_1 = the slow ray of the Berek compensator.
H_2 = the fast ray of the Berek compensator.
e = the extraordinary ray.
o = the ordinary ray.
Length-fast (or negative elongation) = elongation parallel to the vibration direction of the fast ray.
Length-slow (or positive elongation) = elongation parallel to the vibration direction of the slow ray.
ca = circa (about).

CHAPTER II

THE POLARIZING MICROSCOPE

General Discussion.—The polarizing, or the petrographic, microscope, as it may be called, is used to the exclusion of other models in the study of thin sections of minerals and rocks. The lens system is similar to the lens system of the usual modern compound microscope. The instrument, however, contains several additional features that greatly increase its range of usefulness. The most distinctive are the polarizing and analyzing prisms and several accessories such as the Bertrand lens, mica plate, gypsum plate, and quartz wedge.

The names applied to the various parts of a polarizing microscope are given in Fig. 5. The microscope illustrated may be considered either as a student model or as a model designed for routine forms of microscopic work.[1] It is only in cases of advanced research that a more elaborate instrument is required.

The polarizing microscope is adapted for ordinary examination of minerals in plane-polarized light, observation between crossed nicols, and conoscopic study. The lower polarizing prism is left in place beneath the condenser, and the upper prism is moved to one side for ordinary inspection. A full range of magnifications becomes possible with this arrangement. When the microscope is used for examination of specimens between crossed nicols,[2] both prisms are inserted in the path of light. The path of light through the microscope with the latter set-up is shown in the sectional view (Fig. 7). Observation between crossed nicols is

[1] Polarizing microscopes in common use are manufactured by:

Bausch and Lomb Optical Co., Rochester, N.Y.
Carl Zeiss, Inc., 485 Fifth Ave., New York, N.Y.
E. Leitz, Inc., 730 Fifth Ave., New York, N.Y.
Spencer Lens Co., Buffalo, N.Y.

[2] The word *nicol* is frequently used in a broad sense in referring to either the polarizing or the analyzing prisms. The prism used, however, may not be, strictly speaking, a Nicol prism.

possible over the same range of magnifications as that employed for ordinary examination. A simple lens is often inserted above the analyzing prism to correct for the slight change in magnification due to the prism.

Conoscopic study consists of examination between crossed nicols in convergent polarized light with a Bertrand lens. The sequence of units employed for the conoscopic set-up is illustrated

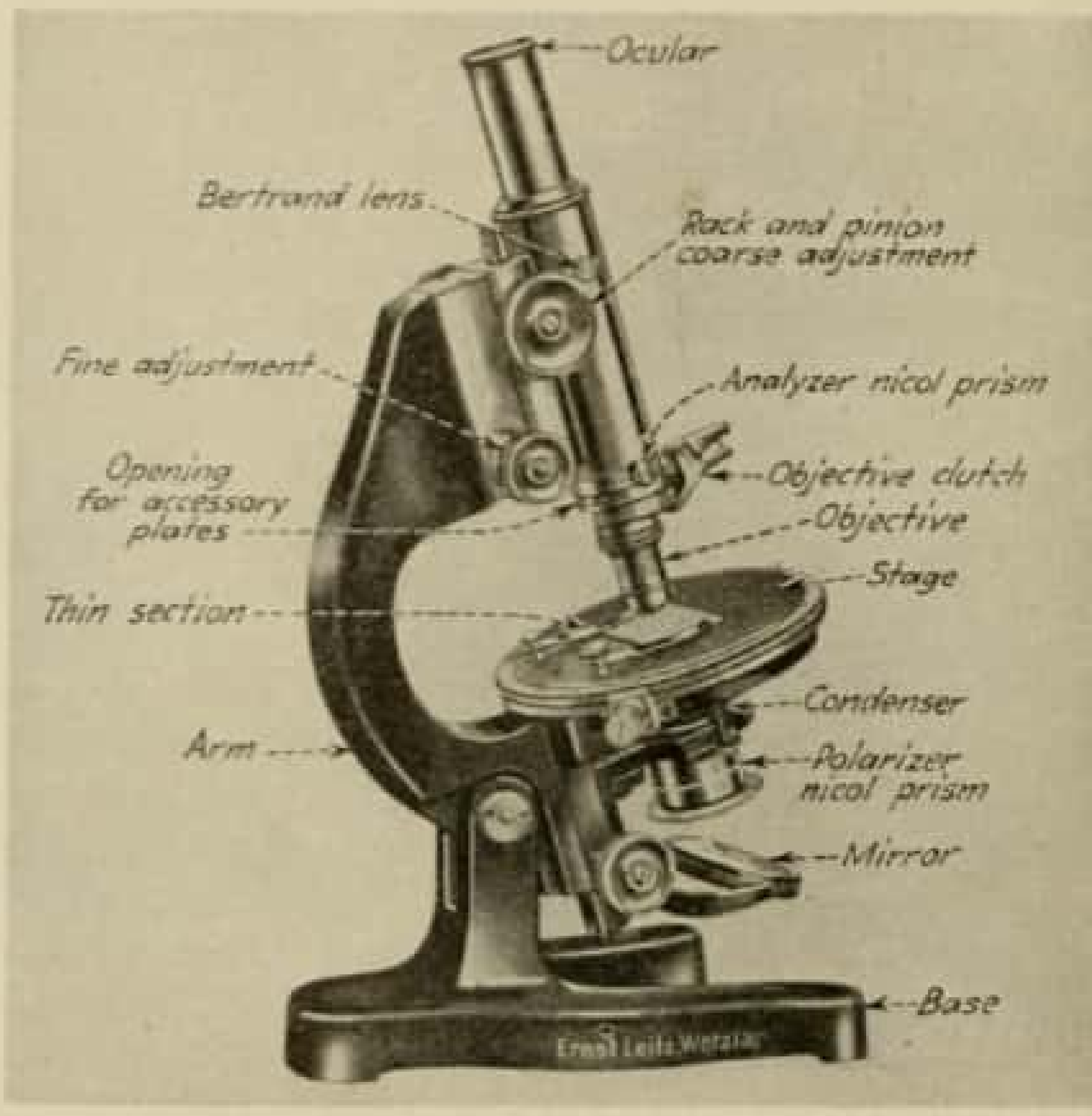


FIG. 5.—A student model petrographic microscope with parts marked. (*E. Leitz, Inc.*)

in Fig. 8. The 16-mm. objective illustrated in the figure is serviceable for crystals of large areas. Ordinarily, either 8- or 4-mm. objectives are used in obtaining interference figures from small crystals.

Parts of the Microscope. *Oculars.*—Oculars used in modern petrographic microscopes are ordinarily of the Huygenian type or a simple modification. In combination with 40- and 16-mm. objectives or other objectives in the same range of magnification, Huygenian oculars are employed. Where combinations giving

higher magnifications are desired, the ocular is similar to the Huygenian ocular but contains a specially corrected eye-lens arrangement giving a flat field. This adjustment is particularly important for photomicrography.

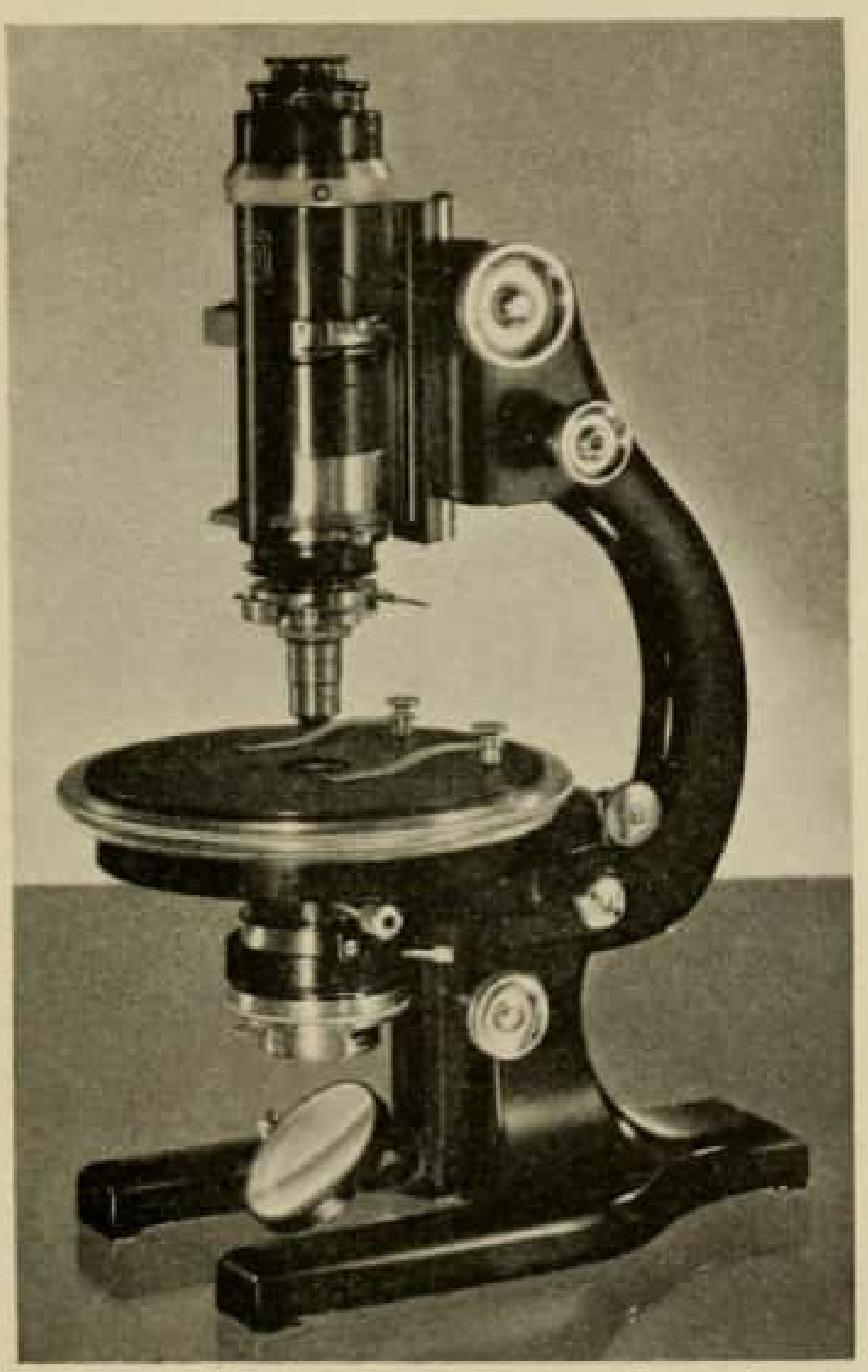


FIG. 6.—A student model polarizing microscope. (*Spencer Lens Company.*)

In the Huygenian ocular the stop is located between the two lenses. An ocular of this type is frequently called a *negative ocular*. The Ramsden ocular with the stop below the two lenses is in contrast described as a *positive ocular*. The arrangement of the stops in the two types is shown in Fig. 9: *a* represents the Huygenian ocular and *b*, the Ramsden type.

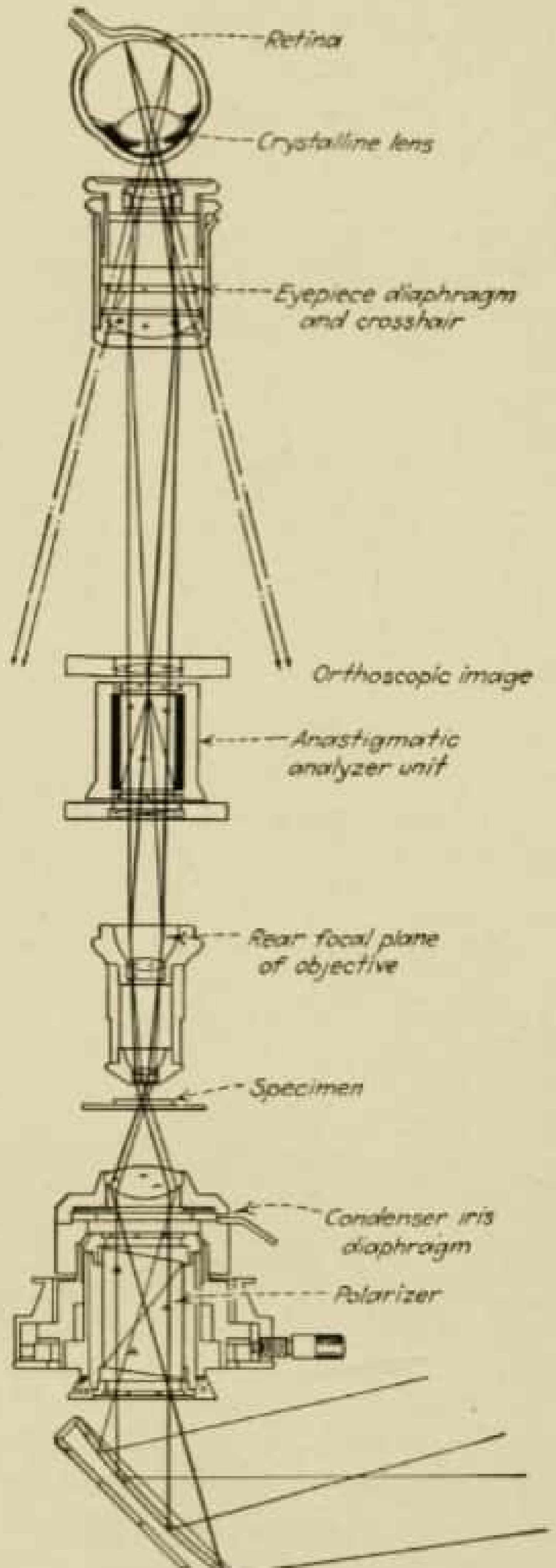


Fig. 7.—A diagram illustrating the path of light through the microscope for ordinary observation with crossed nicols. (*Spencer Lens Company.*)

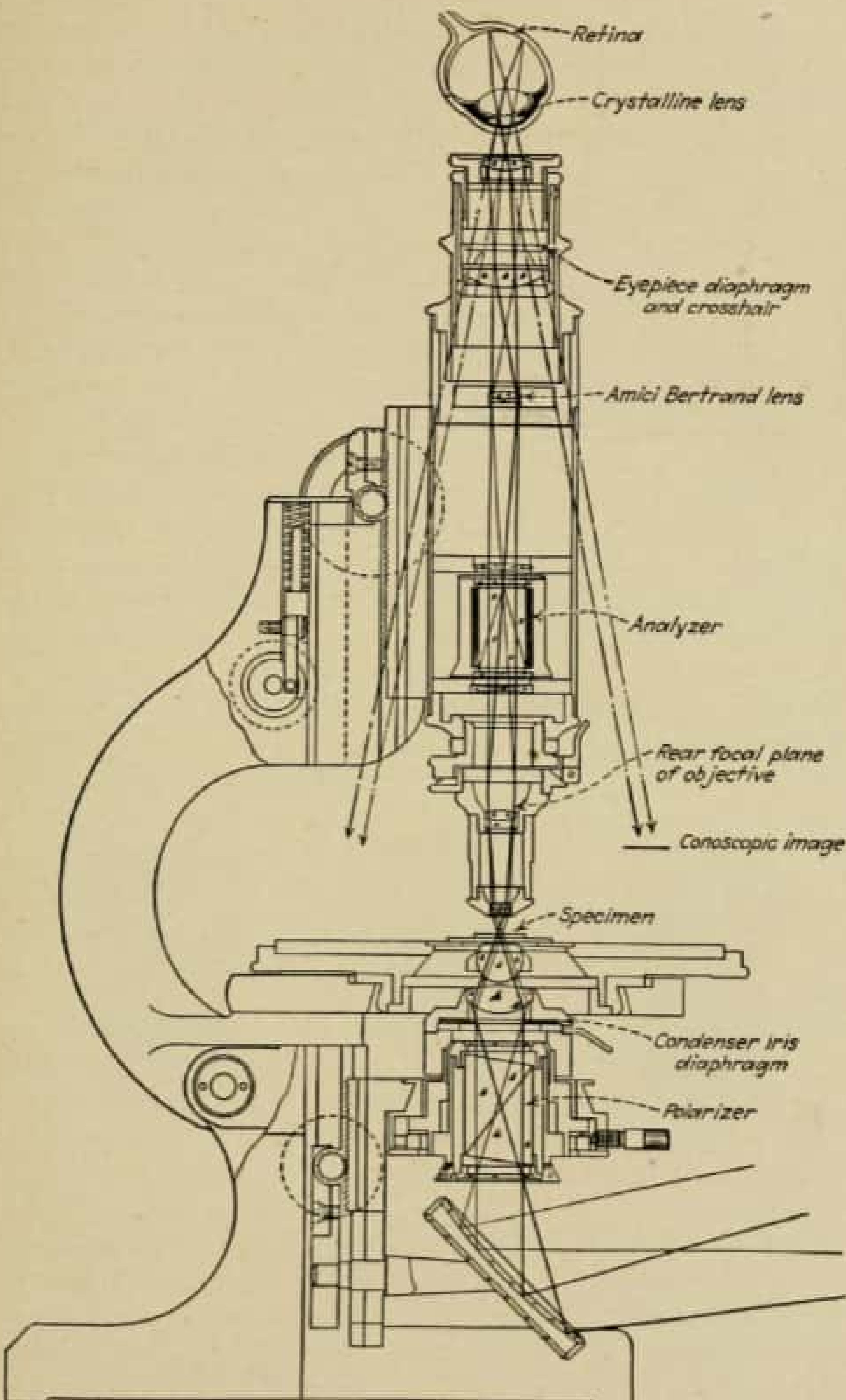
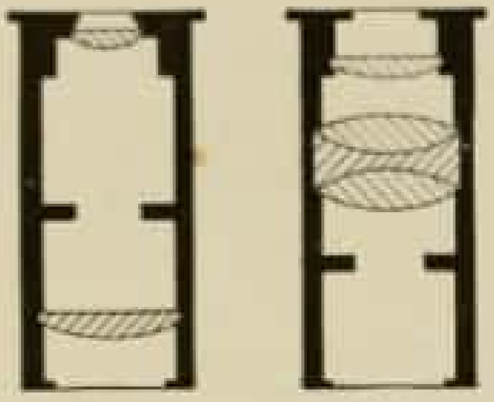


FIG. 8.—A sectional view of the polarizing microscope as a conoscope for the study of interference figures and also for high magnifications. (*Spencer Lens Company.*)

Compensating oculars are constructed to accompany apochromatic objectives. Some manufacturers claim that in order to secure the best results, oculars magnifying more than ten times should be of this type. Ordinary 5 × and 10 × oculars are satisfactory for most work.

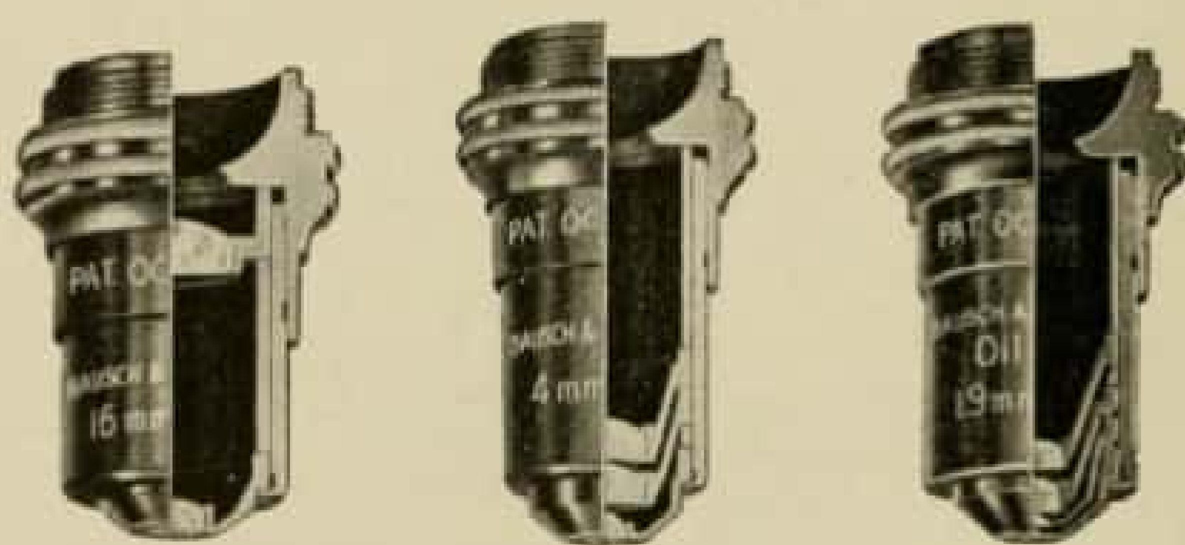


(a) (b)

FIG. 9.—Sections of positive and negative oculars. (a) The Huygenian ocular (a negative ocular). (b) The Ramsden ocular (a positive ocular).

Objectives.—Achromatic objectives are ordinarily used for thin-section or fragment studies. Those usually supplied by the manufacturers as standard equipment, 40-, 32-, 16- and 4-mm. achromatic objectives, will serve for most studies. In the case of achromatic objectives correction of aberrations of the image becomes more difficult with high eyepiece magnification, and only the best achromatic objectives will give satisfactory results with an eyepiece magnification of 12 × or greater. Views of several cut objectives appear in Fig. 10.

Apochromatic objectives have been constructed to provide additional color correction beyond that usually given by achromatic objectives. In this type of objective practically all the



(a) (b) (c)

FIG. 10.—Sectional views of objectives. (a) Achromatic objective 16 mm. (b) Achromatic objective 4 mm. (c) Apochromatic objective 1.9 mm. oil immersion. (*Bausch and Lomb Optical Company.*)

images produced by the different colors of the spectrum lie in the same plane and are equally sharp. The lenses are made of combinations of fluorite and glass. The difficulty of securing good fluorite and the practical difficulties in their manufacture are considerable; consequently the cost is greater than the cost of

ordinary achromatic objectives. However, these objectives are seldom necessary for microscopic study of minerals.

The principal features of an objective that are of interest to the student are the initial magnification, the numerical aperture, the focal length, and the working distance.

The focal length may be employed in determining the approximate initial magnification of an objective. The optical tube length divided by the focal length equals the initial magnification. Several manufacturers stamp the initial magnification for a standard mechanical tube length[1] on the objective. This figure multiplied by the power of the eyepiece gives the magnification for a standard tube length. This should be corrected, however, when the analyzing prism is inserted (unless the prism mount contains a correcting lens). Corrections can be determined by using stage and eyepiece micrometers.

The working distance is the distance between the objective and the top of the cover glass of the microscope slide when the objective is in focus.

The numerical aperture (N. A.) of an objective is a measure of the largest cone of light that it covers from an object point at the principal focus. N. A. equals n sin μ, where n is the index of refraction of the medium between the object under examination and the objective[2] and μ is one-half the angle of the cone of light entering the lens. The numerical aperture furnishes a criterion of the quality of an objective. Other things being equal, at any magnification, the intensity of the image is proportional to N. A.; the resolving power is directly proportional to N. A.; the depth of focus is inversely proportional to N. A. In two objectives having the same focal distance and therefore the same magnification, the one with the greater N. A. will take a larger cone of light from the object and will yield a brighter image. In general, with ordinary lighting, the limit of useful magnification for an average observer is between 500 times the N. A. and 1000 times the N. A.

Oil-immersion objectives are used for high magnifications where a high degree of resolving power and correction are required.

[1] Bausch and Lomb Optical Co. and Spencer Lens Co. = 160 mm. Leitz = 170 mm. Zeiss = 170 mm.

[2] Air (n = 1) in the case of a dry objective and specially prepared cedar oil (n = 1.515) in an oil-immersion objective.

The oil should agree in both dispersive power and index of refraction with the front lens of the objective. The effect of oil immersion on the cone of light entering the front lens of an oil-immersion objective is shown in Fig. 11. A considerable advantage is also gained by placing a drop of oil between the auxiliary condenser lens and the microscope slide. The working distance of an oil-immersion objective is very short; the lenses are difficult to manufacture and are consequently expensive. A good oil-immersion objective, however, gives a beautiful field with high magnification. The objective should be handled carefully, especially in focusing. After use the oil should be removed by the use of lens paper moistened with xylol or benzine.

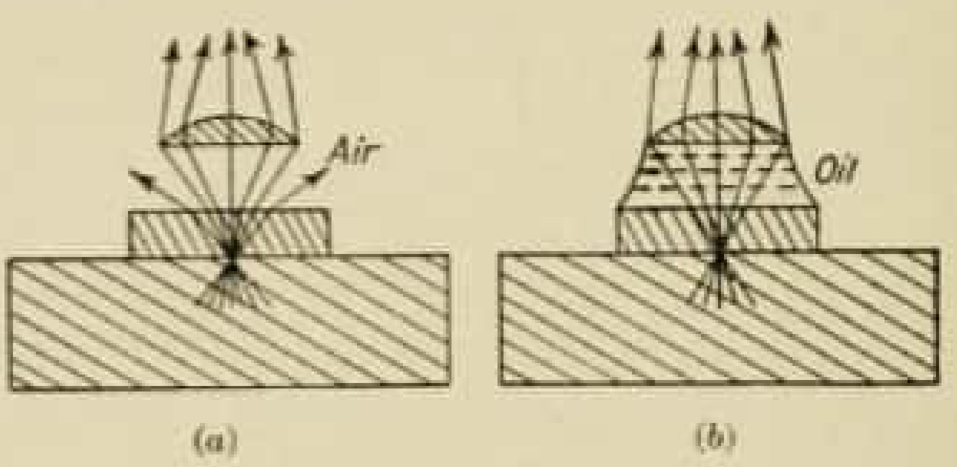


FIG. 11.—Diagram illustrating the convergence of light by means of cedar oil placed in front of the lens of an oil-immersion objective. (a) Air alone without cedar oil; (b) with cedar oil.

Microscope Accessories.—The accessories provided with the microscope generally include a quartz wedge, gypsum plate, and mica plate. These are marked with arrows indicating the fast- and slow-ray vibration directions and are mounted in frames to fit the opening in the tube of the microscope between the objective and the analyzer.

The quartz wedge is ground to produce interference colors from the beginning of the first to the end of the third or fourth order. It is marked and mounted as shown in Fig. 12.

The mica plate and gypsum plate (German = *Glimmer* and *Gips*) together with a centering pin are illustrated in Fig. 13. *N* is the slow-ray direction in the mica and gypsum plates (Leitz microscope).

Analyzer.—The prism mounted in the tube of the microscope above the objective is known as the *analyzer*. It is usually carried on a sliding mount so that it may be inserted or withdrawn from the optical axis at will. The plane of vibration is

usually either perpendicular or horizontal in the field of view. More elaborate microscopes are fitted with a means for rotating the analyzer through 90°.

Polarizer.—The prism mounted in the substage system below the condenser is known as the *polarizer.* It is arranged for

FIG. 12.—The quartz wedge mounted on a glass plate and in a metal frame. (*Spencer Lens Company.*)

any adjustment through 360° but is usually kept adjusted to a plane at right angles to the plane of the analyzer. The position of the polarizer in its mounting is shown in Fig. 15.

Bertrand Lens.—This lens is inserted in the tube of the microscope between the ocular and the analyzer. It serves to bring

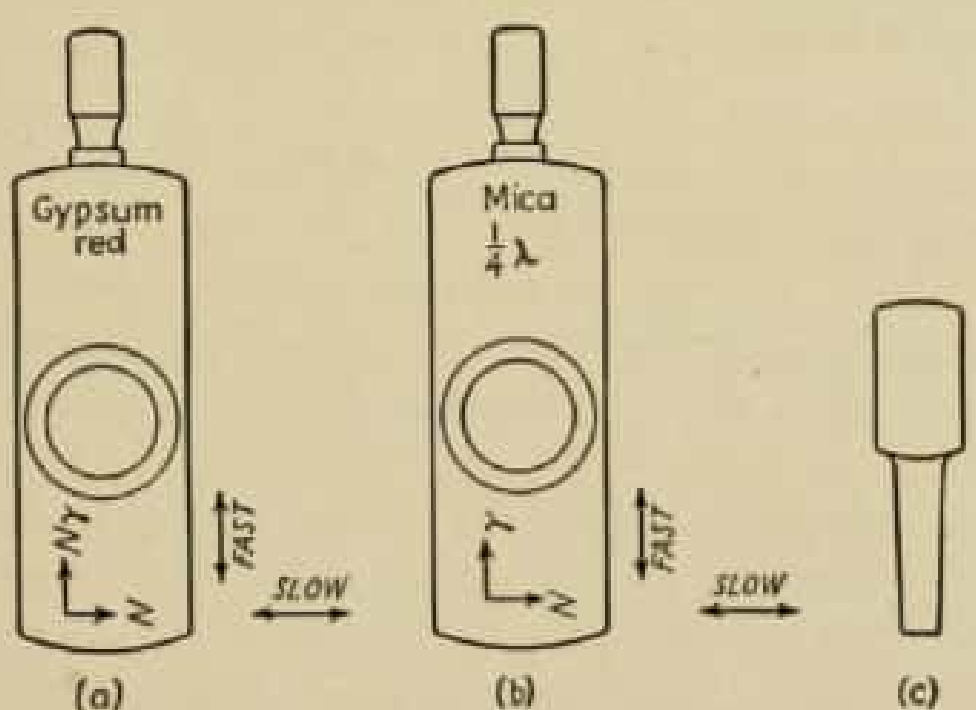


FIG. 13.—The gypsum plate (*a*), mica plate (*b*), and a centering pin (*c*). (*E. Leitz, Inc.*)

the image of an interference figure into the focal plane of the ocular.

Interference figures may be observed without the Bertrand lens if the ocular is removed. For best results, a Bertrand lens

with a focusing diaphragm and an auxiliary magnifier to fit over the eyepiece is used.

Condenser.—Three components may be present in a condenser system of the type selected for illustration. In ordinary examination with low-power objectives a lens component with an illuminating aperture of about 0.22 is used. In working with high power or in obtaining interference figures, another condenser on a movable mounting swings across the axis (Fig. 14). This suffices for all objectives of N. A. up to 1.0. In the case of higher numerical apertures a special lens is inserted in place of the condenser in the movable mounting. This is more effective if used with oil immersion.

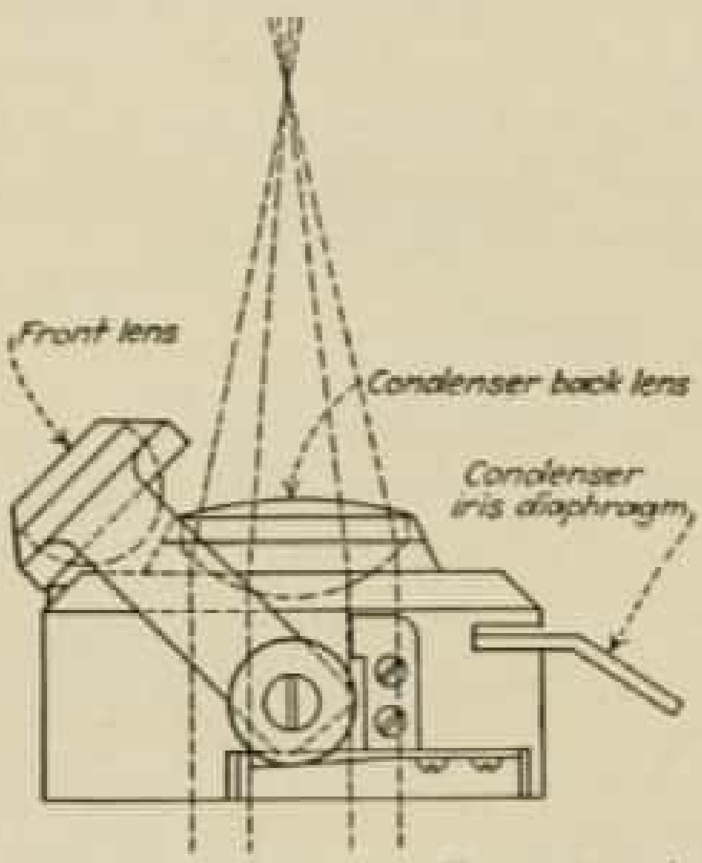


FIG. 14.—A section illustrating the construction of the condenser system. (*Spencer Lens Company.*)

The arrangement of the condenser, together with the various adjustments for the polarizer, is shown in Fig. 15.

Iris Diaphragm.—The iris diaphragm is attached to the lower side of the tube that holds the polarizer. It serves to reduce the cone of light, lessening the illumination of the field of view, and causes objects to stand out with increased relief. The diaphragm is useful in the application of various tests when determining indices of refraction with the microscope.

Mirror.—The mirror is usually reversible, with one surface plane and the other concave. The plane mirror surface is suitable for low-power microscopic work. The concave mirror converges the light upon the object. It is especially useful in high-power examination. It should also be used for low power when the illuminator produces a convergent beam.

Fine Adjustment.—It is advantageous to have the fine adjustment graduated so as to permit the measurement of the displacement of the tube to within 2.5 μ (thousandths of a millimeter). The adjustment is used both for measuring depth and for focusing

on objects at high magnifications. The relationship between a coarse and fine adjustment and the detail of the fine adjustment for one type of microscope are illustrated in Fig. 16.

Berek Compensator.—The compensator is designed to fit the tube slit above the objective in the same opening used for the gypsum and the mica plates. It is employed in the determination of the order of interference colors between crossed nicols.

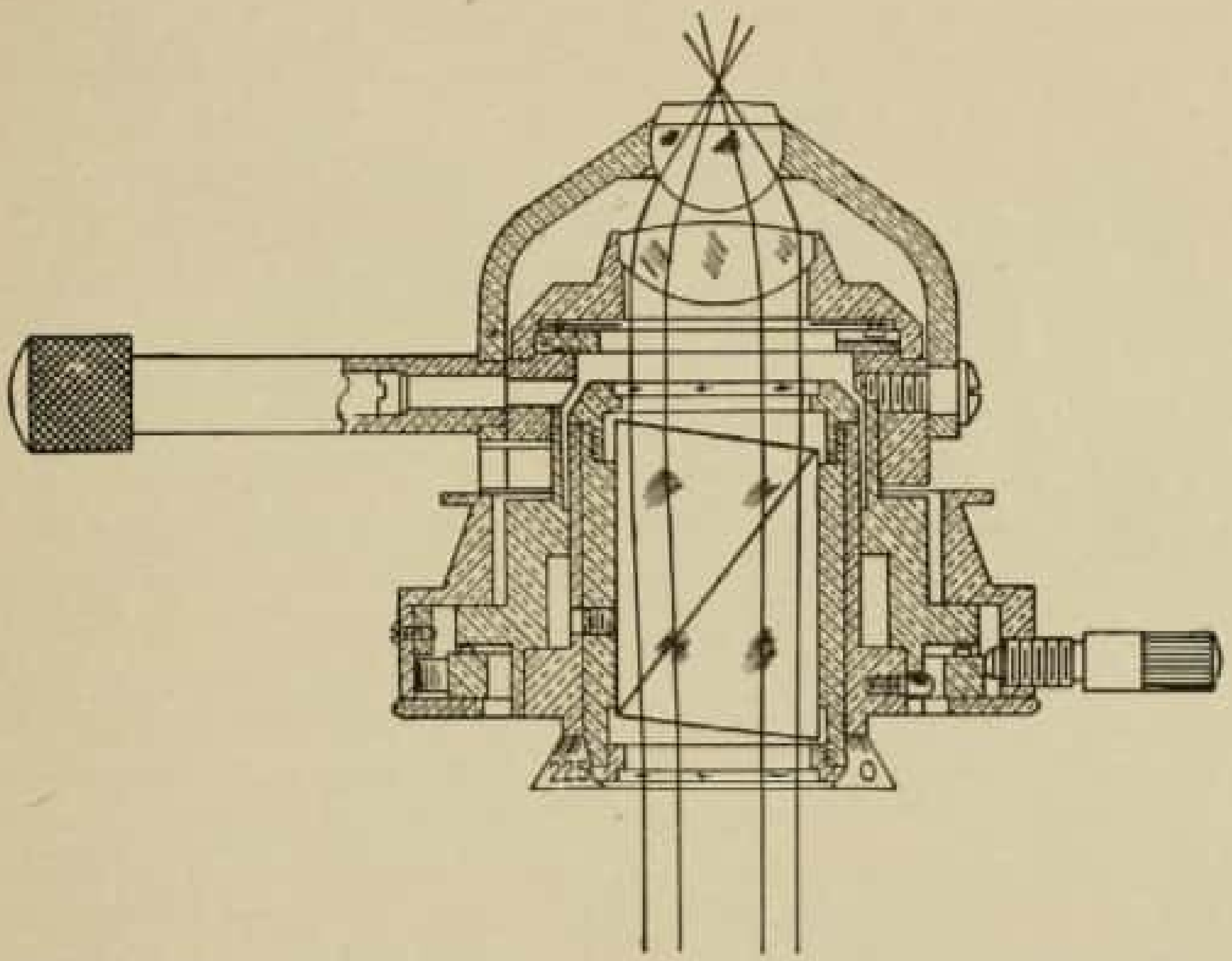


FIG. 15.—The arrangement of the polarizer below the condenser. (*Spencer Lens Company.*)

The plate is inserted with the vibration directions opposed to those of the mineral being examined. The compensator is adjusted until the color of the mineral is neutralized (becomes gray). The amount of adjustment of the compensator necessary to bring this about is a measure of the retardation. A view of the Berek compensator appears in Fig. 17.

Object Slide.—Various lengths and widths of object slides may be used, but the thickness is of greater importance. Immersion condensers are made to work to best advantage with slides from 0.9 to 1.0 mm. thick. Thus slides intended for study at high

magnifications should conform to this thickness if the most satisfactory results are to be secured.

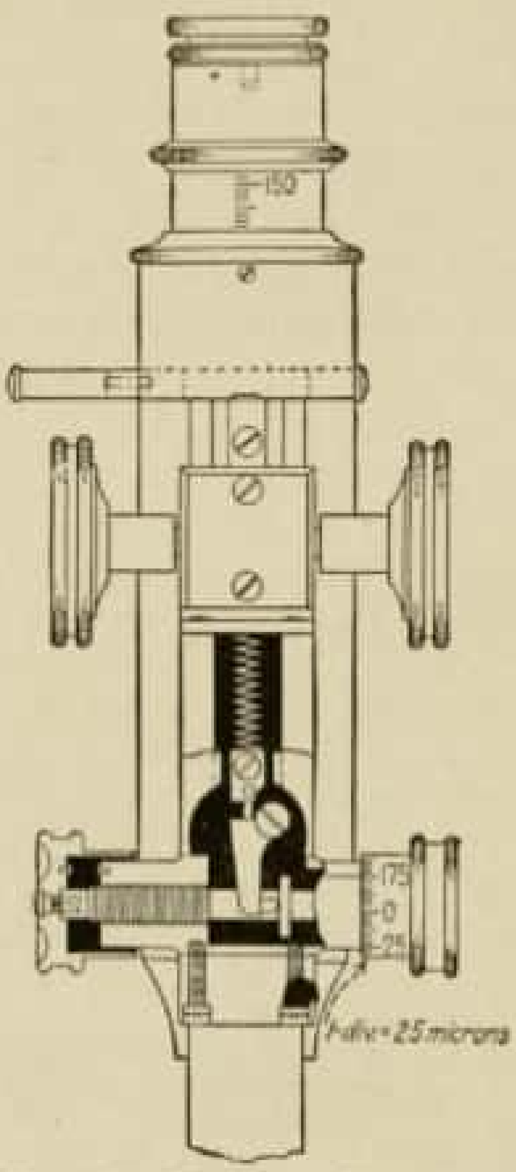


FIG. 16.—The fine adjustment. (*Spencer Lens Company.*)

Slides 26 mm. wide by 45 mm. long are generally used for mounting thin sections of minerals and rocks. Such slides fit easily on the rotating stage of the polarizing microscope yet are large enough to contain a good-sized slice and also a label of suitable dimensions. Long slides usually employed in biological investigations may be quite inconvenient on a rotating stage.

Cover Glass.—Objectives usually employed for thin-section work are corrected by the manufacturers for a cover-glass thickness of from 0.15 to 0.17 mm. It is assumed that the top of the slice is pressed directly against the bottom of the cover glass. In case the slide is poorly mounted and a space intervenes between the top of the slice and the bottom of the cover glass the extra distance should be considered as so much additional thickness of cover glass. In order to obtain the best results with objectives, cover glasses of standard thickness should be employed.

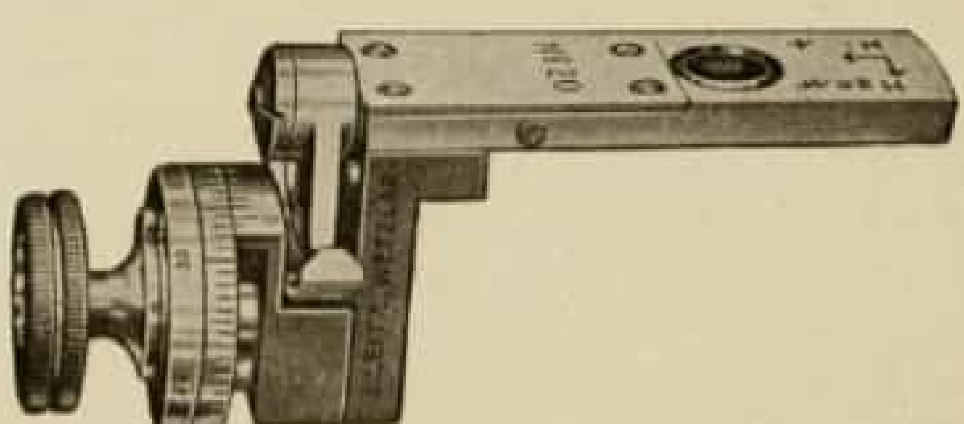


FIG. 17.—The Berek compensator. (*E. Leitz, Inc.*)

Precautions to Be Observed in the Use of the Microscope.—Even under the best conditions microscope work produces a

certain amount of strain upon the eyes. It is essential, therefore, to employ the best possible conditions of work in order to reduce such strain to a minimum.

The student should assume an erect but not too rigid position. Such a position with the microscope tube inclined allows him to work with maximum comfort.

Both eyes should be kept open while looking through the instrument. If it is difficult to do this at first, a shield should be placed over the eye not in use. A binocular eye guard is illustrated in Fig. 18. A spring-clamp ring for attachment to the

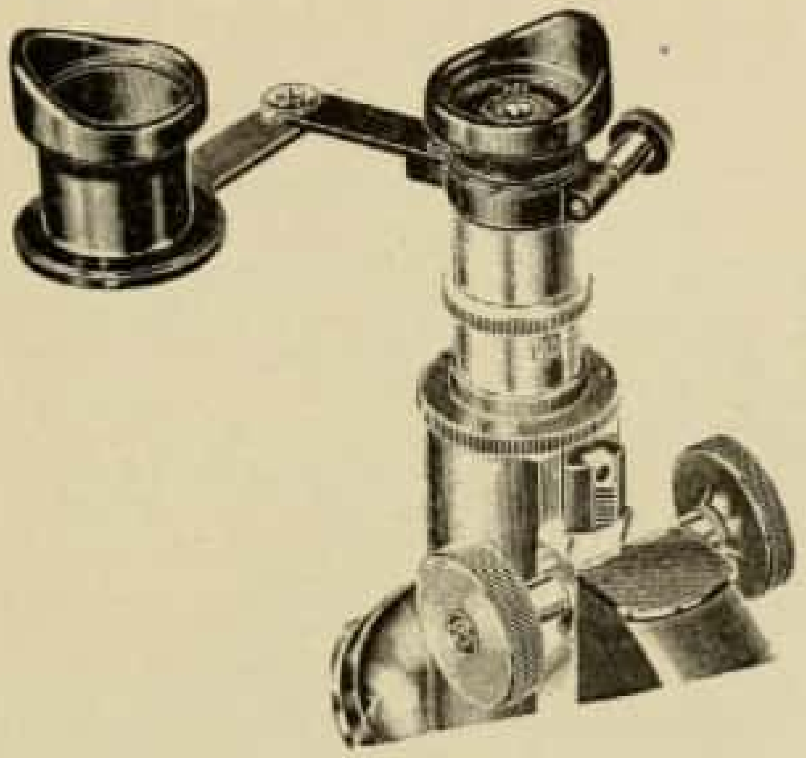


FIG. 18.—A binocular eye guard for the unused eye in microscope work.

microscope tube carries a lateral-jointed arm with a dummy eyepiece for covering the unused eye. It is also a good plan to learn to observe equally well with either eye and not to develop the so-called *microscope eye*.

In laboratories requiring a large amount of routine microscopic work an attachment known as the *euscope* has been devised for projecting the image of the field on a small shielded viewing screen. The observer is seated directly in front of the screen and looks forward into a viewing box with the image on a screen at the opposite end, as shown in Fig. 19.

The euscope has several applications for routine work. A ground glass may be inserted on the front of the instrument and used for microprojection. Grating lines may be ruled on the ground glass corresponding to the divisions of a stage microm-

eter, in which case the euscope will serve for microscopic measurement of grain size. The instrument is also adapted to hold a camera for taking photomicrographs of thin sections.

Care of the Instrument.—A polarizing microscope is an expensive piece of equipment. Properly used, it should last a lifetime. If not handled carefully, it may become useless with very little real service. Most of the precautions to be observed in the use of the instrument are such as should be applied to any piece of fine apparatus. A few, however, are of special nature and should be definitely mentioned.

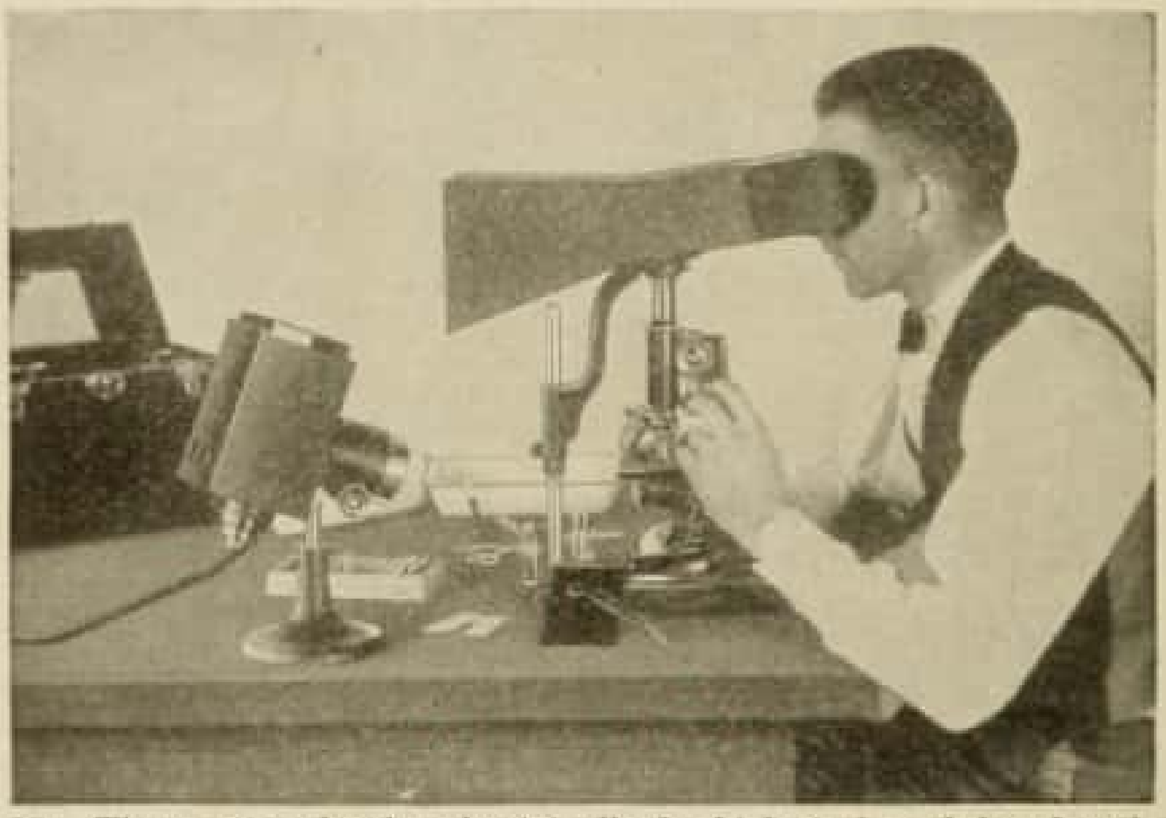


FIG. 19.—The euscope developed originally for biological work but found to be useful for mineralogical work as well. (*Bausch and Lomb Optical Company.*)

Fine-textured lens paper, or, still better, a camel's-hair brush, should be used for cleaning all optical parts. This applies to the ocular, the objectives, the substage system, the mirror, and the two nicols.

Objectives should be brought into focus by moving the tube of the microscope upward rather than downward. Possibility of contact between the lower lens of the objective and the thin section is thus avoided. High-power or oil-immersion objectives should be cleaned with lens paper and xylol or benzine (not alcohol).

Chemicals should not be used on the stage unless special precautions are taken to protect the objective. Objectives may be protected by the use of cover glasses fastened to the lower

lens. Occasionally an old objective is reserved for chemical work alone.

Magnification.—The microscope is primarily an instrument for magnification. It is worth while, therefore, to form at the outset an idea of the enlargement of the field of view with the various lens systems available. The following table outlines the various magnifications at the eye for different combinations of objectives with an equivalent focus of 40, 32, 16, 8, 4, and 2 mm. (oil immersion) and also oculars magnifying five, ten, and fifteen times, respectively.

MAGNIFICATIONS[1]

Type of objective	Equivalent focus, millimeters	Magnification number	Magnifications with oculars			Working distance, millimeters	N. A.
			5×	10×	15×		
Achromatic........	40	3.2	16	32	48	34.5	0.12
Achromatic........	32	4.3	22	43	65	27.0	0.15
Achromatic........	16	10	50	100	150	5.8	0.25
Apochromatic......	8	23	115	230	345	0.85	0.65
Apochromatic......	4	46	230	460	690	0.20	0.95
Apochromatic (oil immersion)......	2	92	460	920	1380	0.11	1.32

Tube length: 170 mm.
Image distance: 250 mm.
[1] After Leitz.

There are certain definite limits to the resolving power of the microscope, even with the best lens systems available. As long as the increase in magnification results in better vision of an object and more definite separation of detail, the magnification may be said to be "useful." When the object merely becomes larger without any increase in resolving power, the magnification is "empty." So-called, *empty* magnifications of great magnitude are possible.

For practical purposes the upper limit of "useful" magnification with the polarizing microscope is about 1800:1.[1] Larger

[1] An oil-immersion objective (Carl Zeiss) primary magnification 120, N. A. 1.3, free working distance 0.08 mm., in combination with a 15 × ocular, should yield a magnification ratio of 1800:1.

magnifications, as usually reported, are the result of some form of projection or special equipment in which the exact limits of useful magnification are not clearly known. The most ordinary form of projection is the enlargement employed in taking photomicrographs. Photomicrographs taken with a camera having a long bellows may increase the magnification ratio given by the microscope several times. Thus magnification ratios of 3000:1, 4000:1, or even considerably higher may be obtained. Such increase in magnification above the magnification of the microscope is essentially enlargement and does not result in increase in resolution. From the standpoint of increase in resolution or detail, it is "empty" magnification. Enlarged photomicrographs of this type, however, may have value for purposes of demonstration.

The limit of resolution for green light with a lens of N. A. 1.40 is said to be approximately 0.18 μ. This might be described as the distance apart of two object points in the field of view of the microscope whose disc images would just touch as projected to the eye. It has been shown mathematically that the limit of resolution equals the wave length divided by twice the numerical aperture. From this relationship it is possible to compute the number of lines per inch that can be separated by different numerical apertures. Several may be given as follows for blue light wave length 486:

N. A.	Lines per Inch Separated
1.30	136,000
0.85	89,000
0.65	68,000
0.30	31,000

An accurate check of the magnification of the field of view in the microscope can be obtained by using a stage micrometer (Fig. 20). The stage micrometer is a glass slide carefully ruled into hundredths of a millimeter. It not only serves as a comparison object for determining the magnification of the microscope but also may be used to give the magnification of micro drawings, of micro projections, and of photomicrographs.

Micrometer eyepieces are also utilized when the dimensions of particular objects in the field of view are desired (Fig. 21*a*). Such eyepieces are useful in determining the axial angle of inter-

ference figures with the microscope. The eyepieces should be calibrated with the aid of the stage micrometers for various objectives. The dimensions represented by the divisions in the micrometer ocular (Fig. 21*b*) as observed at the eye are governed by relations between the objective, the eyepiece, the tube length, and by the presence or absence in the optical train of the analyzer.

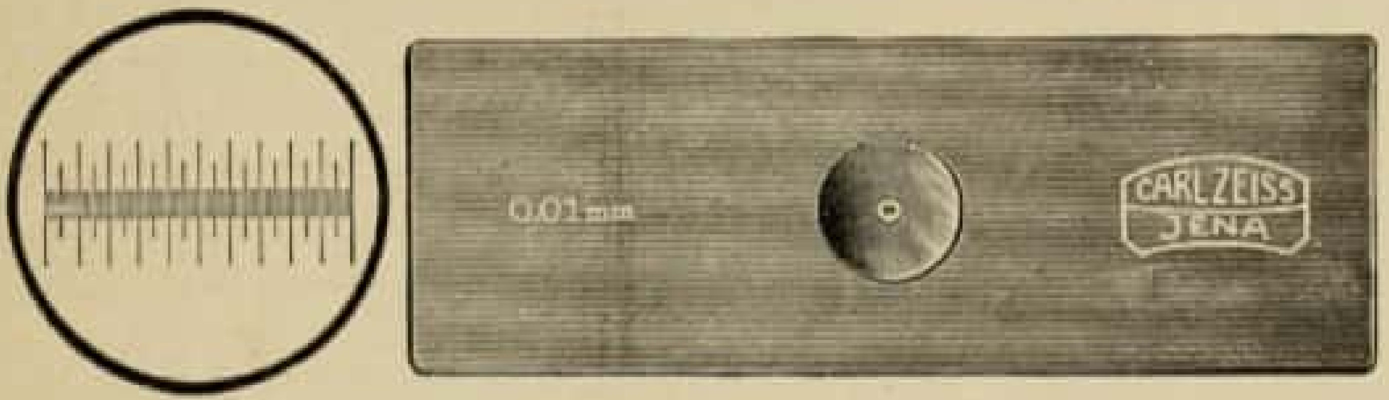


FIG. 20.—The stage micrometer. (*Carl Zeiss, Inc.*)

Micrometer eyepieces of the grating type (Fig. 21*c*) are employed to measure the areas of grains or fragments in the microscope field. These are also calibrated for different lens combinations with a stage micrometer.

Illumination.—At ordinary magnifications a good north light with a broad, clear sky forms an excellent source of illumination for the polarizing microscope.

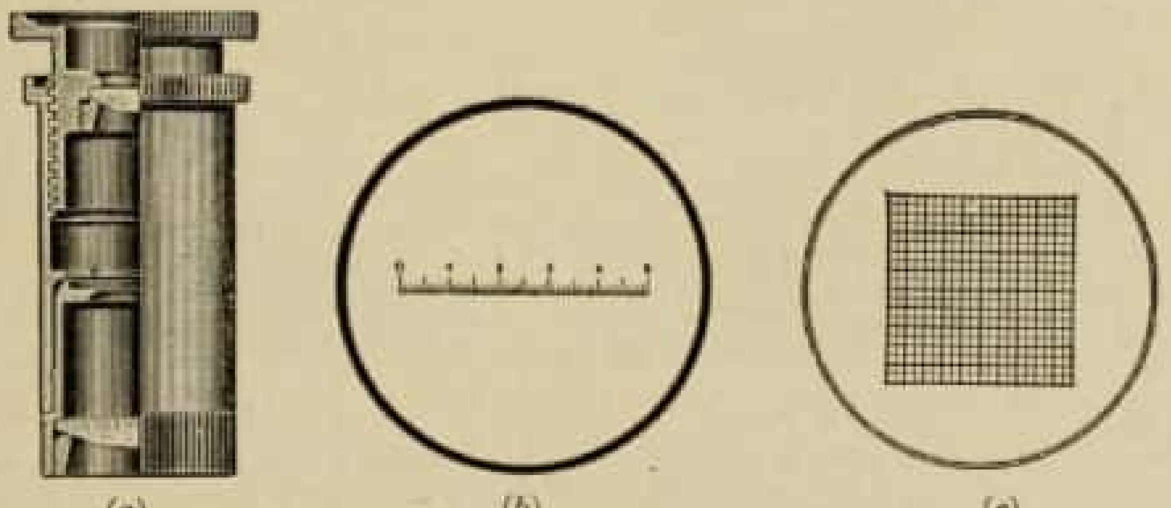
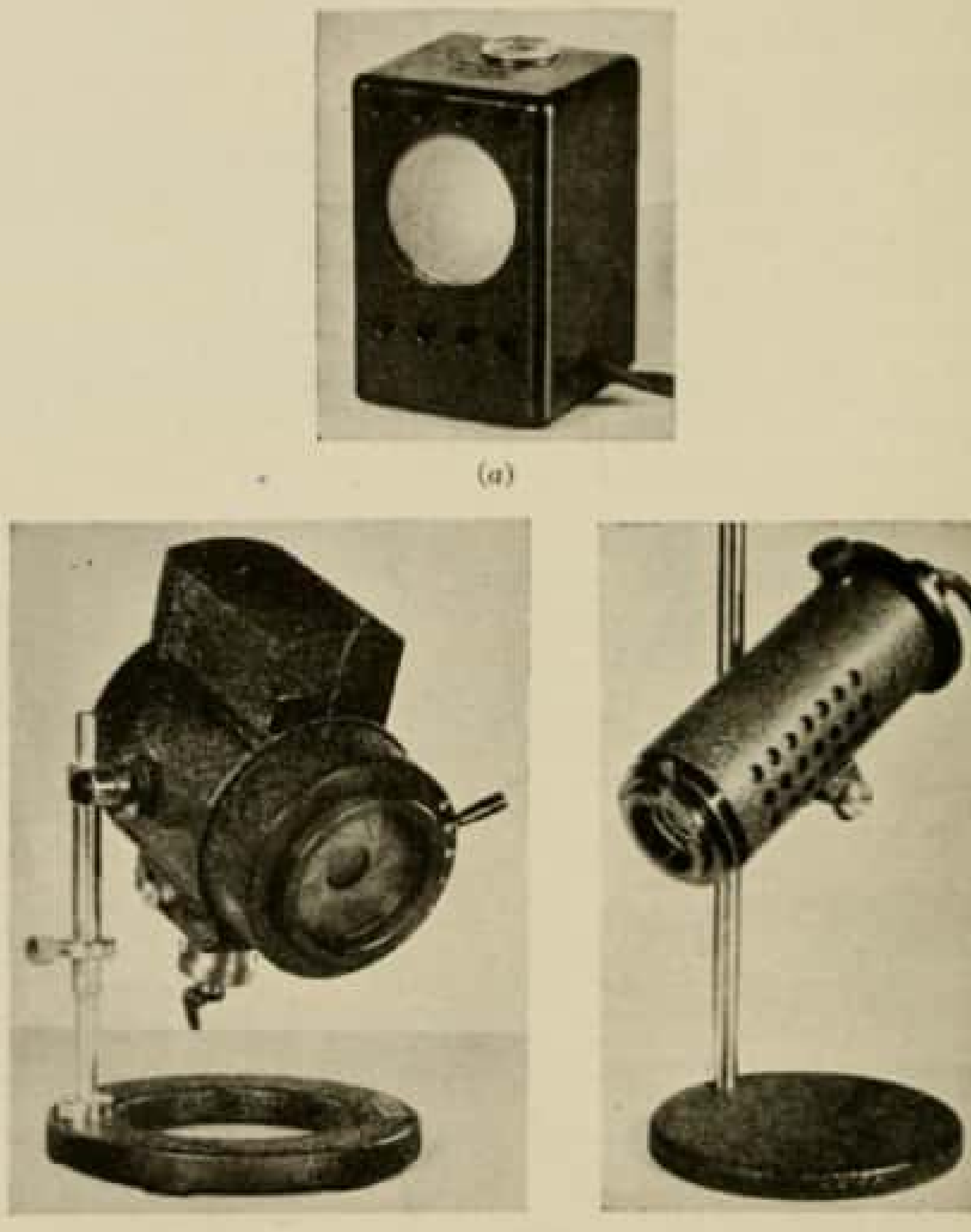


FIG. 21.—(*a*) Micrometer ocular; (*b*) scale in a micrometer ocular; (*c*) grating micrometer. (*Carl Zeiss, Inc.*)

In case such illumination is not available, artificial daylight lights can be successfully employed. These consist of various types of electric bulbs mounted in cases with a special blue-glass light filter in the path of the illumination. Three types are illustrated in Fig. 22. A low-voltage bulb with a condensing lens

and diaphragm, as illustrated in Fig. 22*c*, provides suitable illumination for a wide variety of magnifications.

At high magnifications and for photomicrographic work a mechanical-feed arc lamp is sometimes used. The beam from



(*a*)

(*b*) (*c*)

FIG. 22.—Various types of artificial illumination for the microscope: (*a*) small substage lamp; (*b*) strong lamp for general utility; (*c*) a low voltage light with a wide range of intensity. ((*a*), (*b*), *Spencer Lens Co.* (*c*) *Eric Sobotka.*)

the arc is very warm and should always be passed through a cooling cell of water in order to avoid injuring the cement in the prisms of the microscope (unless special prisms are employed).

Regardless of the source of illumination employed, it is important to regulate the light entering the microscope with respect to the optical system if the best results are to be achieved. In

Optical mineralogy ..

order properly to accomplish this result, suitable filters should be available for the source of illumination, the light used should be equipped with an iris diaphragm, and the condenser system should also contain a suitable diaphragm. The field of view in the microscope should be carefully bounded by each diaphragm and the proper filter system employed to reduce the illumination to suitable intensity. Proper resolution for each magnification may be secured in this way.

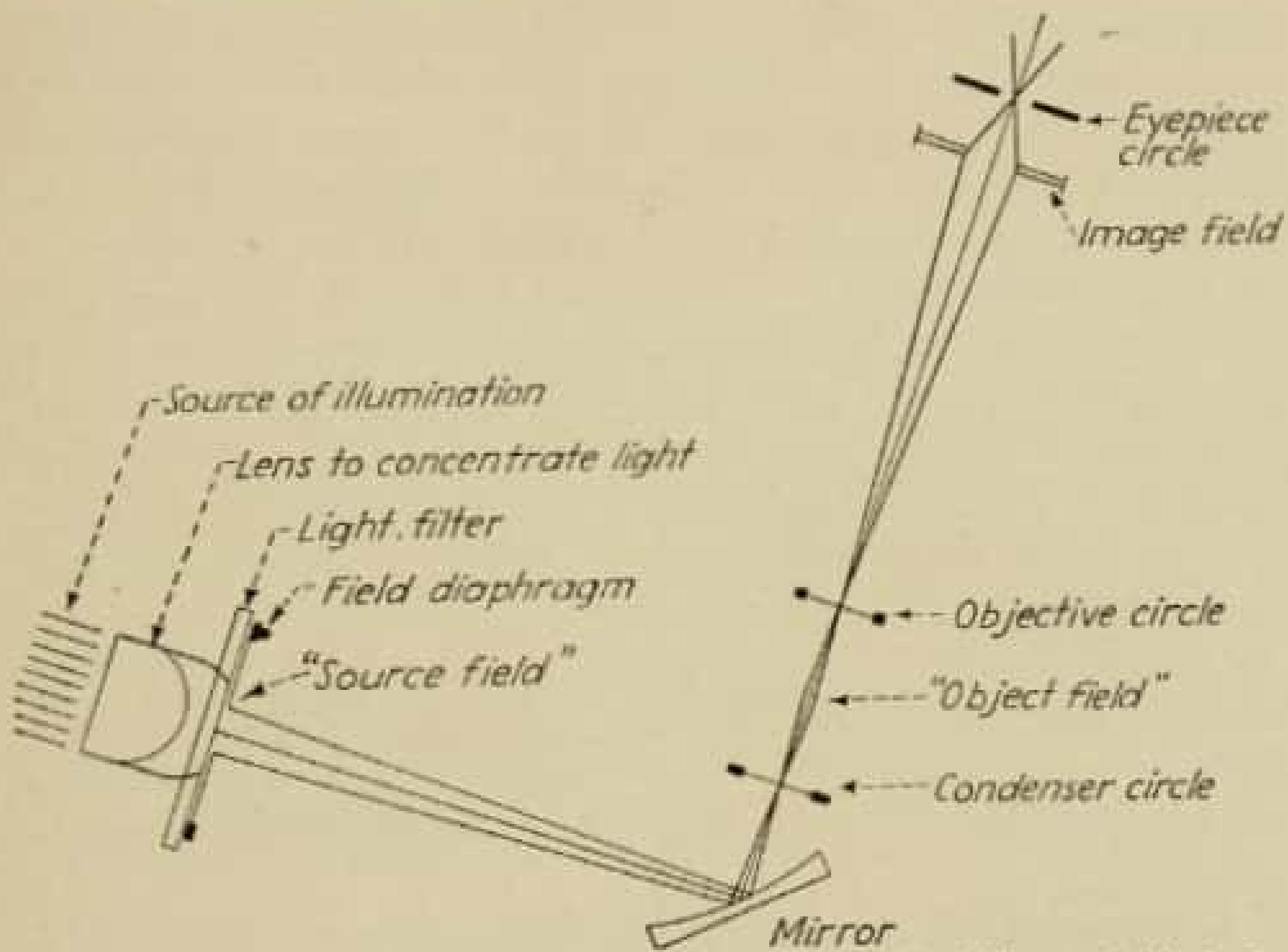


FIG. 23.—Diagram showing the relative dimensions of the different fields in the microscope and their relation to the illumination. (*After Belling.*)

The circular field of view seen by the observer when he looks through the microscope is bounded primarily by the diaphragm of the eyepiece. The diaphragm is fixed and also contains the crosshairs. The magnified image of this diaphragm bounds the *image field* seen through the eyepiece. The *object field* is a field of view equal in diameter to the diameter of the image field divided by the total magnification. It measures the area of the thin section or other object under observation at a particular instant. The *source field* is the field of view at the glass filter of the illuminator. The diameter of the source field is equal to the product of the diameter of the object field and the reciprocal of the reduction caused by the condenser. In the control of

illumination, the area of the light leaving the illuminator should be cut by the condenser until it equals the source field. When the light entering the microscope is limited in this way, only the circle of the object that is seen is illuminated, and glare due to the interference of marginal light is eliminated.

When the condenser is in focus, the iris diaphragm determines the used aperture of the condenser. It is important that this aperture be filled with uniform illumination. If the objective is placed in focus and the eyepiece removed, the used aperture of the condenser may be observed by looking down the tube of the microscope. This may be termed the *condenser circle*. It is a bright circular area encircled by a dimly lighted band or ring. The latter is sometimes termed the *objective circle*. The objective circle is not bounded by a diaphragm but is limited by the margin of the objective lenses. In microscopic adjustment, it has been found that the condenser circle should be as nearly equal to the objective circle in diameter as possible without causing glare. This is particularly important in using objectives yielding high initial magnification with correspondingly high numerical apertures. Oil-immersion objectives usually require the use of immersion condensers in order to avoid the loss of useful magnification free from glare. Either corrected water or oil-immersion condensers may be used. The N. A. of the condenser should be less than the N. A. of the objective by a small amount.

Adjustment of the Polarizing Microscope.—Four separate steps can be outlined as necessary to arrange the polarizing microscope in order for the examination of rock sections:

1. Centering the stage with the field.
2. Crossing the nicols.
3. Testing the crosshairs.
4. Determining the vibration plane of the lower nicol.

1. *Centering the Stage with the Field.*—The stage is centered when the axis of rotation coincides with the tube axis of the microscope, the tube axis standing perpendicular to the center of the field of view. Screws on the side of either the objective collar or the stage (Fig. 24) are used to align the tube axis and the stage. A simple procedure is followed. While looking through the instrument at the field of view, pick out an easily recognizable point, and then rotate the stage. The point should

describe a concentric circle of rotation about the intersection of the crosshairs. If it does not, rotate the stage until the point is farthest from the intersection of the crosshairs, bring it in halfway by means of the centering screws, and then bring it to the center of the stage by actually moving the slide itself. Rotate the stage, and repeat the operation if the centering has not been completed the first time.

2. *Crossing the Nicols.*—The planes of vibration of the two prisms should be set at right angles to each other. The plane of vibration of the analyzer is usually fixed by the manufacturer either from left to right or up and down as one observes the microscopic field. The lower nicol is adjusted at right angles by

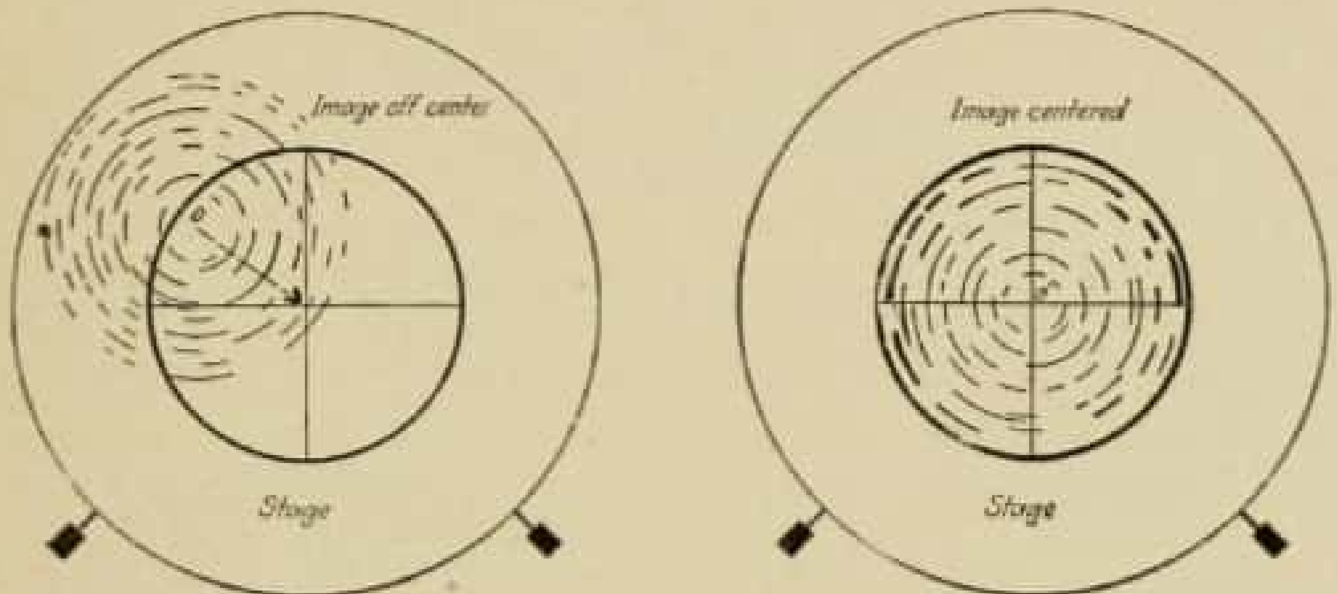


Fig. 24.—Diagram illustrating centering the field of view in the microscope.

rotating it in the substage collar until the field becomes dark, with both nicols in the path of light. The nicols should remain in the position giving maximum darkness. A small pin usually fits into a notch at this position.

3. *Testing the Crosshairs.*—The crosshairs in the ocular may be either the spiderweb type or lines engraved on a glass plate. In either case it is important that the hair lines be parallel to the planes of vibration of the two nicols. Ordinarily these are set by the optical firm supplying the microscope, and the ocular is so arranged that it will not fit the tube of the microscope in other than the correct position. The adjustment should be checked occasionally, however, and in case the alignment is inaccurate, the crosshairs should be reset by an experienced technician.

A slide containing small elongated rectangular crystals of natrolite (Fig. 25) is useful to test the setting of the crosshairs

with the planes of the nicols.[1] The natrolite becomes dark between crossed nicols when the edges of the crystals are parallel to the vibration directions. A slide containing a small natrolite

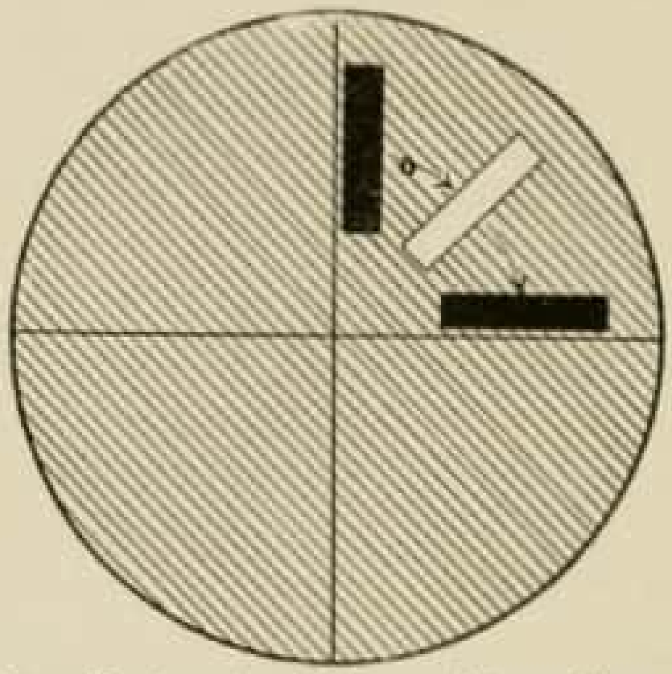


FIG. 25.—Testing the adjustments of the crosshairs with natrolite fragments.

crystal may be placed upon the stage between crossed nicols and turned until it becomes dark. If the crosshairs are in adjust-

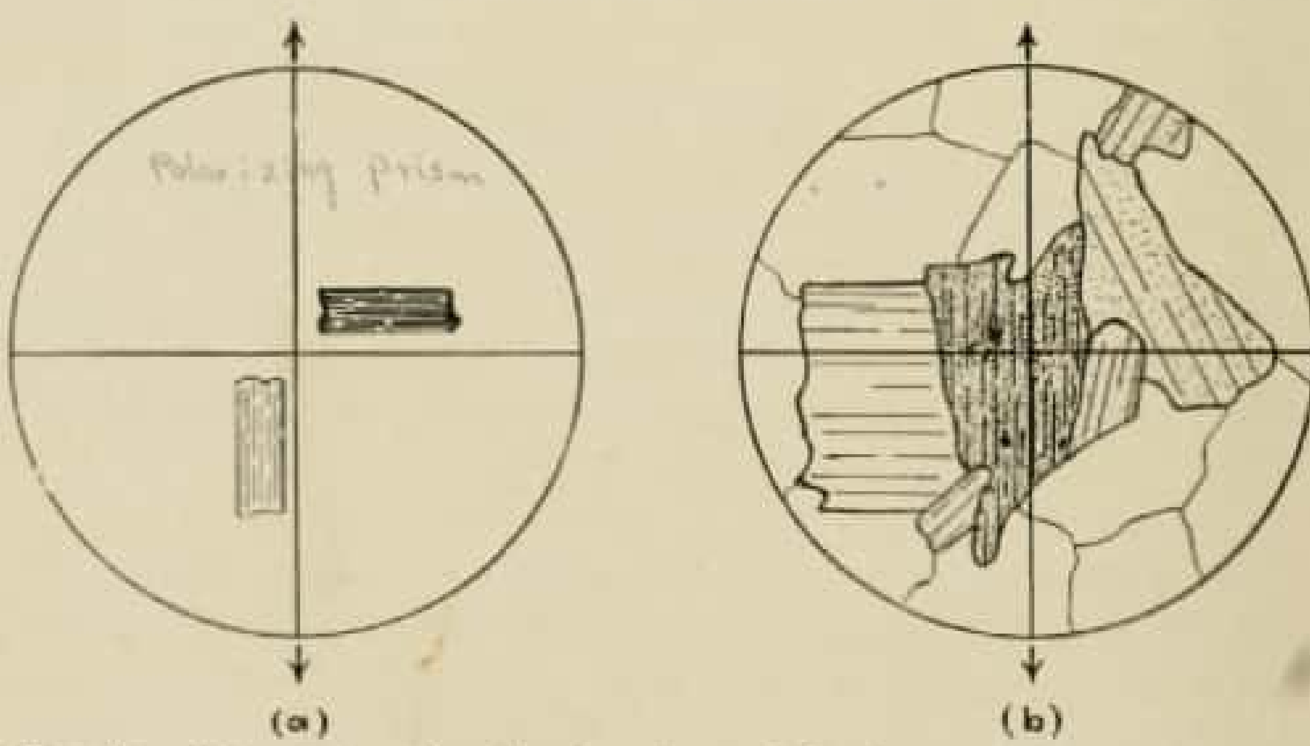


FIG. 26.—Determining the vibration plane of the lower nicol: (*a*) elongated tourmaline fragments; (*b*) biotite in thin section.

ment, the web lines should be parallel or at right angles to the straight lines of the crystal. This is true in each of the four

[1] If natrolite is not available, any crystalline material with straight-line edges and parallel extinction may be substituted.

positions of extinction. In 45° intermediate positions the natrolite will show maximum illumination.

4. *Determining the Vibration Plane of the Lower Nicol.*—After the other adjustments have been made, the vibration direction of the lower nicol can be determined with either fibrous tourmaline fragments or a rock section containing biotite showing cleavage.

Tourmaline (Fig. 26*a*) has maximum absorption when it is oriented with the *c*-axis (usually the long direction of a crystal or fragment) in a direction at right angles to the plane of vibration of the polarizing prism. Biotite (Fig. 26*b*), on the other hand, is darkest when the cleavage is parallel to the vibration direction. Note the positions of greatest and least darkness, observing with the upper nicol thrown out from the tube. These indicate either the vibration direction or the normal to the vibration direction, depending upon whether the slide is biotite or tourmaline.

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Much useful information may be obtained from the catalogues of various optical firms:

Bausch and Lomb Optical Co., Rochester, N.Y.
E. Leitz, Inc., 730 Fifth Ave., New York.
Spencer Lens Co., Buffalo, N.Y.
Carl Zeiss, Inc., 485 Fifth Ave., New York.

CHAPTER V

PLANE POLARIZED LIGHT IN MINERALS

Polarized Light.—In the foregoing it has been assumed for descriptive purposes that light may be considered as wave motion. This condition holds for ordinary white light or for monochromatic light of any sort. It is also assumed that the vibrations take place in all directions around the line of transmission. Under certain conditions, however, the tendency to vibrate in all directions around the line of transmission is modified, and the waves become restricted for the most part to a single direction of vibration. When its vibration direction is thus restricted, light is said to be *polarized*.

Polarization of light may be brought about in several ways: (1) by reflection from a polished surface; (2) by repeated refraction at an angle through several plates of thin glass; (3) by absorption by certain crystals such as tourmaline or herapathite; (4) by specially constructed prisms of optically clear calcite.

Polarization by Reflection.—Light reflected obliquely from a polished surface, such as a table top, is partially polarized. If the reflection is examined through a rotating nicol prism, the field of view in the prism will darken whenever the vibration plane of the nicol is at right angles to the plane of reflection of the polished surface.

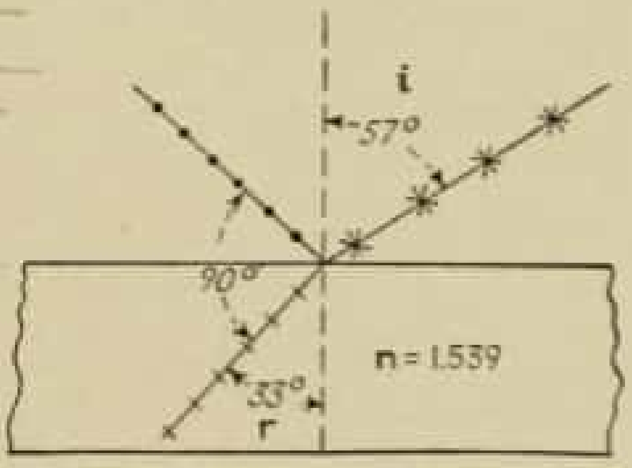

FIG. 46.—Polarization by reflection.

Light reflected and refracted obliquely from mirrors is partially polarized. According to Brewster, the polarization in the case of a glass plate is a maximum when the directions of reflection and refraction are 90° apart (Fig. 46). When these two directions are at such an angle, the angle r becomes the complement of the angle i, and the formula $n = \sin i/\sin r$ may be written $\sin i/\cos i = \tan i = n$. Thus, at the angle of maximum polar-

Thin crystals of a strongly absorptive compound, iodo-cinchonidine-sulfate, were described in 1852 by William Bird Herapath, M.D. (Fig. 49). Because of their strong absorption in one direction corresponding to the behavior of tourmaline, the crystals were referred to as "artificial tourmalines." The material was subsequently called *herapathite* in honor of the discoverer. More recently, methods have been developed for producing thin transparent sheets containing small crystals of herapathite in parallel orientation embedded in a plastic binder. The effect corresponds in a general way to that of a single crystal of large area, and a polarizing sheet results. Two overlapping sheets of this material are illustrated in Fig. 50. It is possible to prepare such polarizing sheets covering several square feet in area.

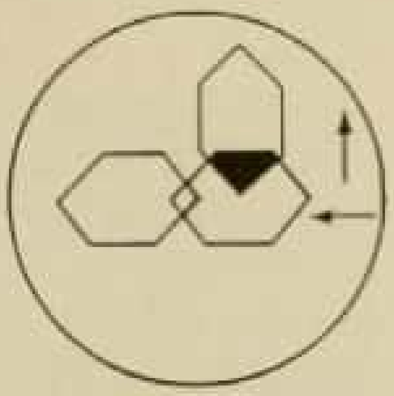

Fig. 49.—Crystals of herapathite showing an area of extinction where individuals with directions of greatest absorption at right angles are superimposed. (*After Herapath*, 1853.)

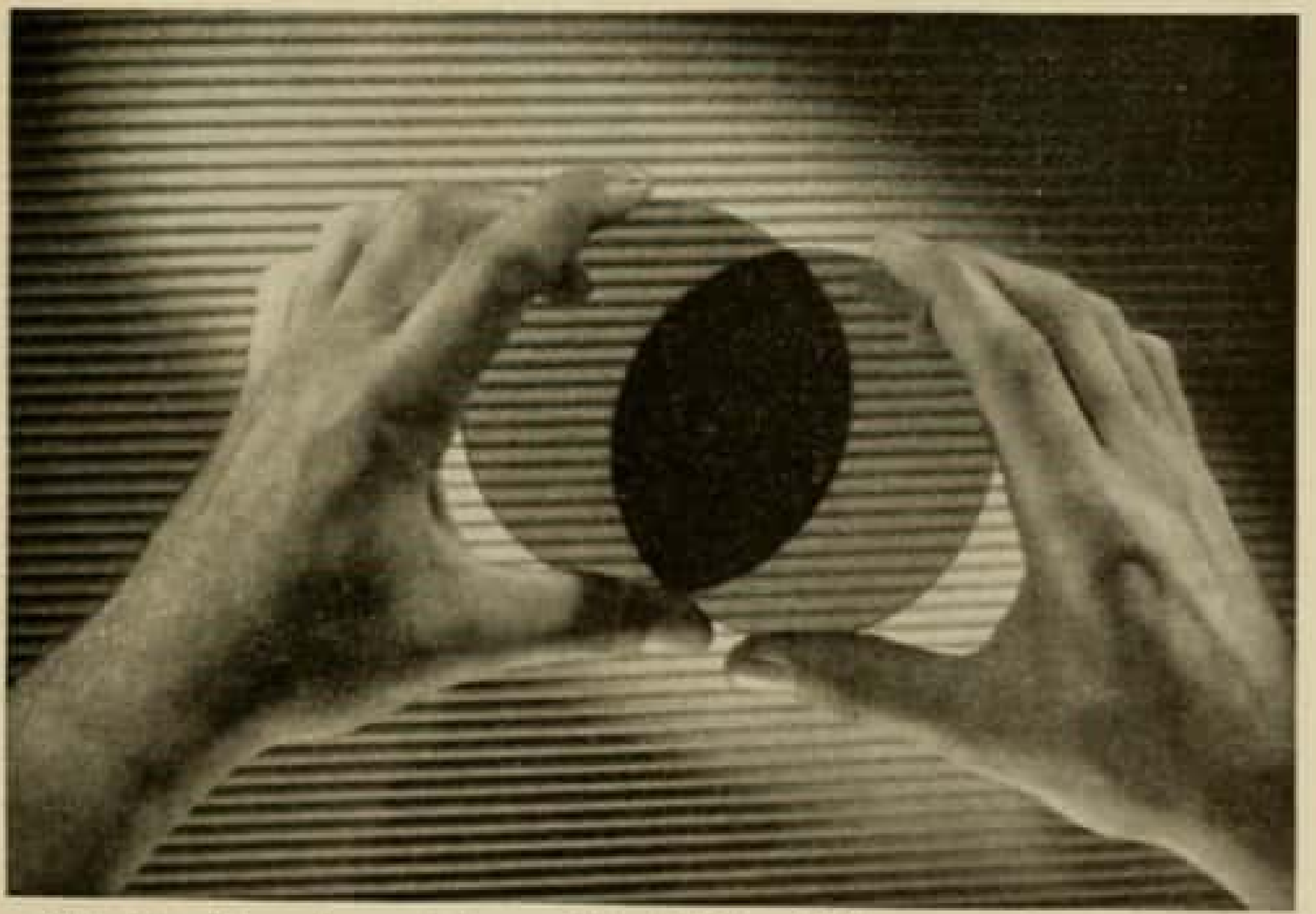

Fig. 50.—Two discs of herapathite ("Polaroid") mounted on glass plates photographed with the planes of polarization at right angles. (*Courtesy of the Polarizing Instrument Company.*)

Up to the present time, because of low absorption in the violet, polarizing sheets have not been substituted for optically clear

calcite in the polarizing microscope. Such sheets are excellent, however, for optical demonstration and for many supplementary uses, particularly where a wide field of polarized light is required.

Double Refraction (Birefringence).—Although polarization results when light is transmitted through most transparent minerals, the phenomenon is not ordinarily accompanied by absorption. With a few exceptions, light in passing through transparent minerals is doubly refracted into two beams vibrating along two planes that are approximately at right angles to each other.[1] This applies except in the case of amorphous minerals and minerals crystallizing in the isometric system.

The most obvious illustration of double refraction and accompanying polarization by a mineral occurs in transparent calcite, or Iceland spar. Objects viewed through a cleavage plate of Iceland spar appear double; if a cleavage face of calcite is placed over a dot within a circle marked on a piece of paper, the dot will appear to the eye as two dots and the circle as two circles (Fig. 51). The light giving rise to one image will be composed of waves vibrating parallel to the long diagonal; that giving rise to the other will be composed of waves vibrating parallel to the short one. The two light rays have been differently refracted, and the indices of refraction are different.

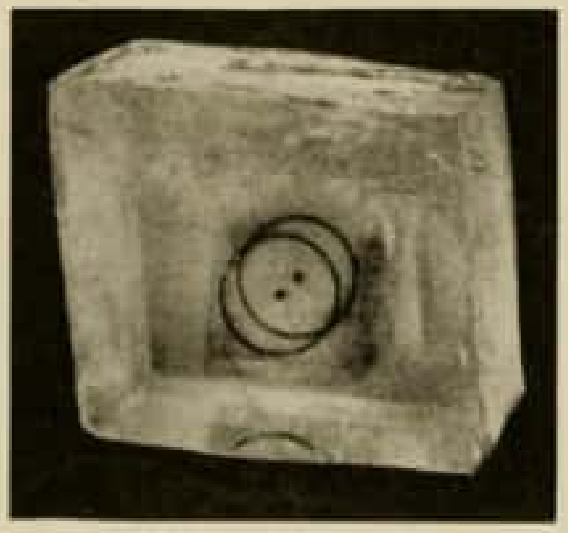

FIG. 51.—Double refraction illustrated by a cleavage rhomb of transparent calcite or Iceland spar.

The cleavage form of calcite, the rhombohedron, is illustrated in Fig. 51 with the principal axis in the vertical position. If the opposite vertices of the calcite cleavage having threefold symmetry are ground to triangular surfaces and polished, light may be passed directly through parallel to the principal crystallographic axis [perpendicular to (0001)]. The light rays vibrate

[1] F. E. Wright has demonstrated that the precise determination of the angle between the two rays is a matter of careful physical measurement. In discussing double refraction, the amount of variation from 90° will not be taken into account, and the two rays will be considered in simple terms as about at right angles.

ization the tangent of the angle of incidence equals the index of refraction of the reflecting substance. Consequently, when the index of refraction of the substance is known, the angle of maximum polarization may be obtained from a table of tangents. The angular relationships for a plate $n = 1.539$ are shown in Fig. 46. Figure 47 is a sectional view of an old-fashioned polariscope employing reflection from glass plates to obtain polarized light. The instrument was used before the advent of the modern polarizing microscope to produce polarized light for the study of mineral plates.

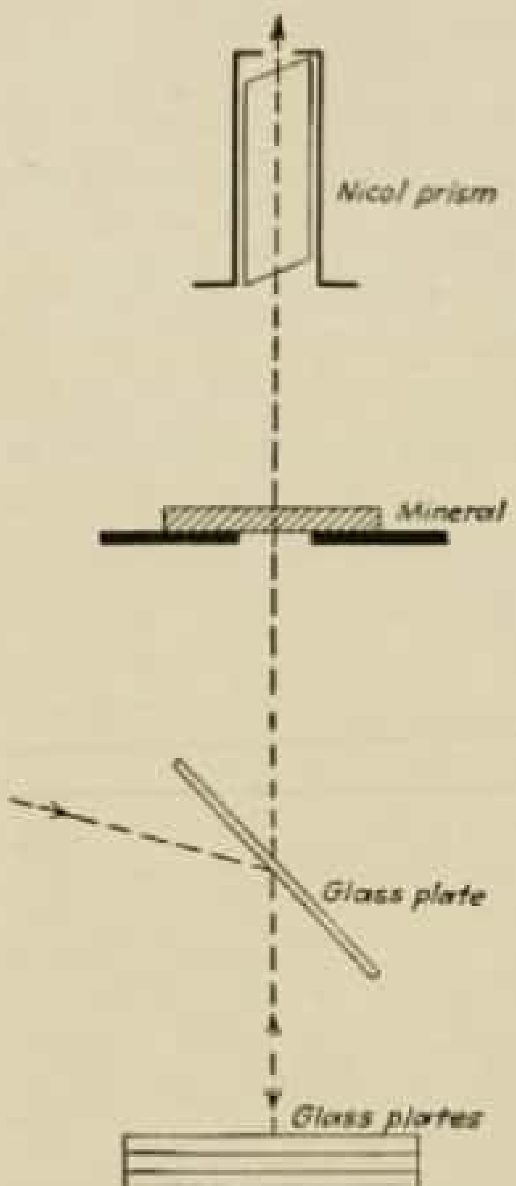

Fig. 47.—Polarization by reflection in a polariscope.

Polarization by Absorption.—Tourmaline has the property of producing polarization by absorption. Light that strikes the crystal vibrating in a variety of planes is strongly absorbed except along one plane. As a result, the rays of light that emerge are limited to this plane of vibration and are thus plane polarized. The crystallographic axis c, frequently the long direction of the crystal, lies parallel to the plane of vibration.

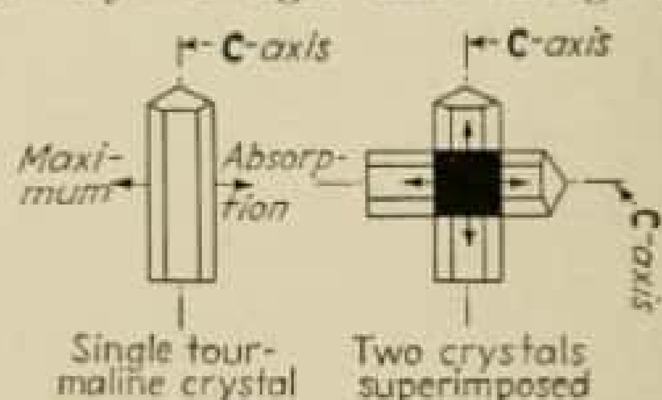

Fig. 48.—Darkness due to absorption produced by two superimposed tourmaline crystals.

Observation through either a Nicol prism or another plate of tourmaline cut in a similar fashion effectively reveals the polarization. When the plane of the nicol is at right angles to the optic axis of the tourmaline plate, the crystal appears dark. Also, when the directions of the two superimposed tourmaline plates are at right angles to each other, the overlapping portion is dark (Fig. 48).

uniformly about this axis, and there is an absence of double refraction. This is the optic axis in either hexagonal or tetragonal crystals and agrees in direction with the principal crystallographic axis (the *c*-axis).

If light passing along the optic axis is examined by means of a Nicol prism, it is found that there is no double refraction and the mineral appears isotropic. In any other direction, however, double refraction results. In the latter cases light is polarized into two rays vibrating at right angles to each other, one vibrating at right angles to the optic axis, the other in a plane through the optic axis. The former is known as the *ordinary ray;* the latter

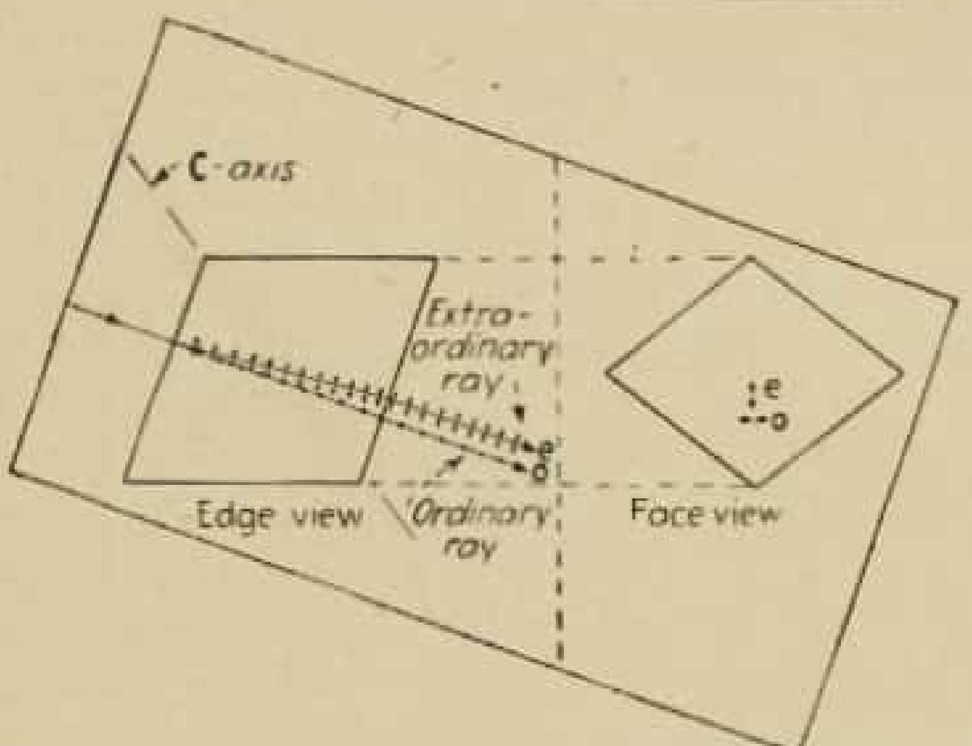

FIG. 52.—Edge and face views of a cleavage rhombohedron of calcite illustrating double refraction.

is called the *extraordinary ray.* The ordinary ray vibrates in a direction at right angles to the optic axis and parallel to the long diagonals of the rhombic faces of the cleavage rhombohedron as shown in Fig. 52. The extraordinary ray vibrates in a plane passing through the optic axis and also passing through the short diagonal. In some minerals the extraordinary ray is the fast ray; in others it is the slow ray.

Nicol Prism.—The Nicol prisms in the polarizing microscope utilize the principle of double refraction to produce polarized light. Optically clear calcite is used, and a prism is made of two parts cemented together with Canada balsam. The two halves form a prism of the type illustrated in Fig. 54. Light entering the base of the prism is broken into extraordinary and

ordinary rays. The extraordinary ray has an index of refraction $n = 1.516$ at the angle of incidence for the prism; the ordinary ray has an index of refraction $n = 1.658$. The index of the extraordinary ray is close to the index of refraction of balsam, $n = 1.537$. The index of the ordinary ray, however, is considerably greater. Both rays strike the cementing plane of balsam obliquely. The obliquity of the ordinary ray exceeds the critical angle between the ordinary ray and balsam. As a result, it is not refracted through the balsam but is reflected to the side of the prism. Since the extraordinary ray does not exceed the

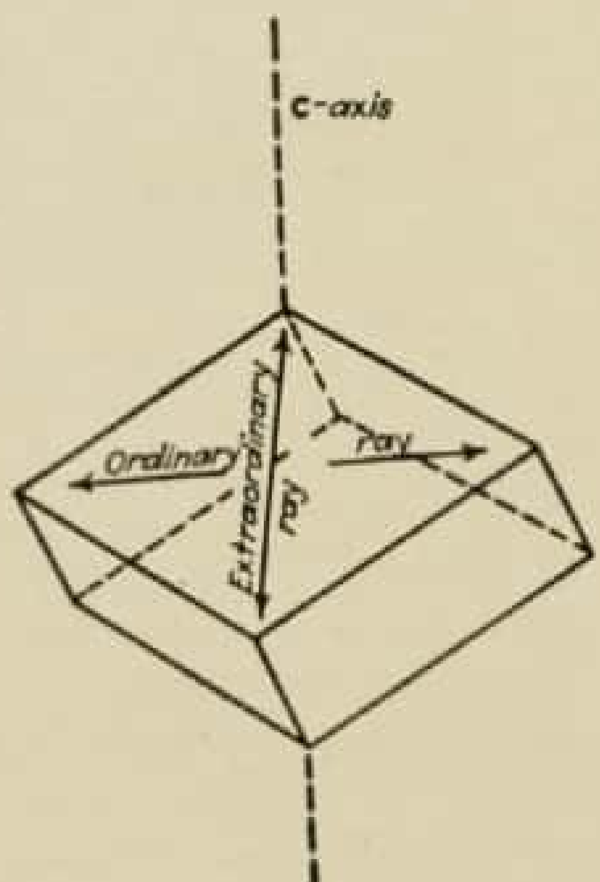

FIG. 53.—The extraordinary and ordinary rays in a calcite cleavage.

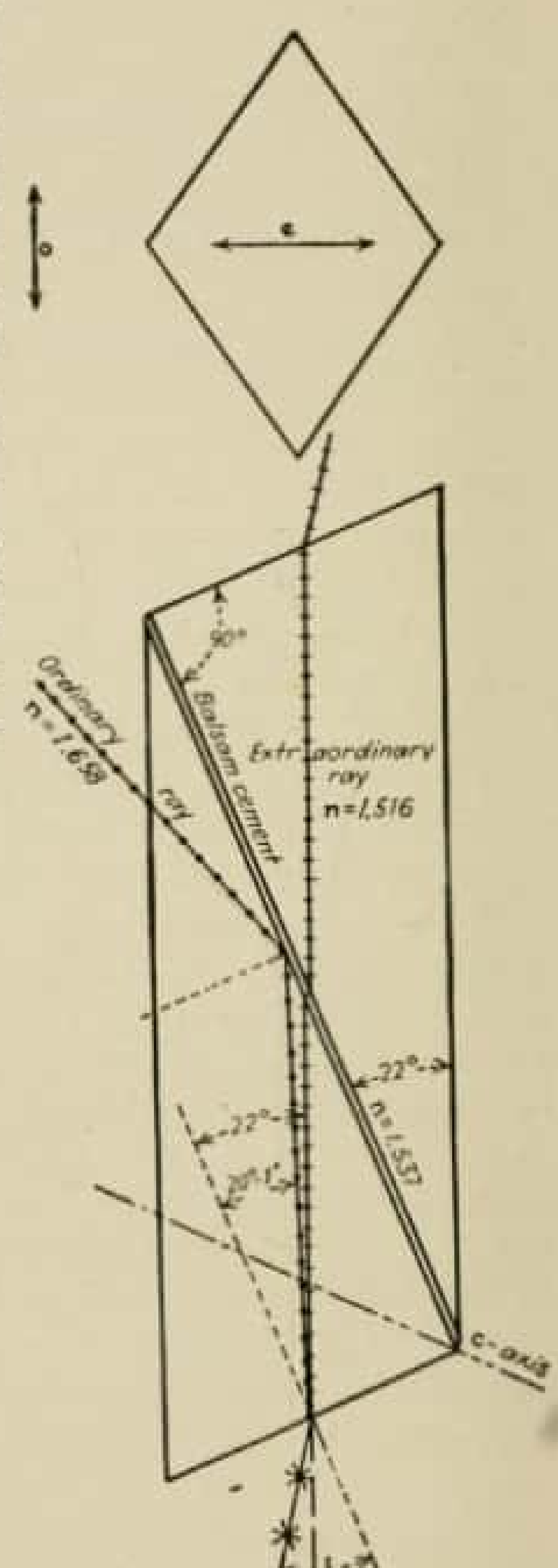

FIG. 54.—The polarization and deviation of light in a Nicol prism.

critical angle between the extraordinary ray and balsam, it passes on through the prism with little deviation.

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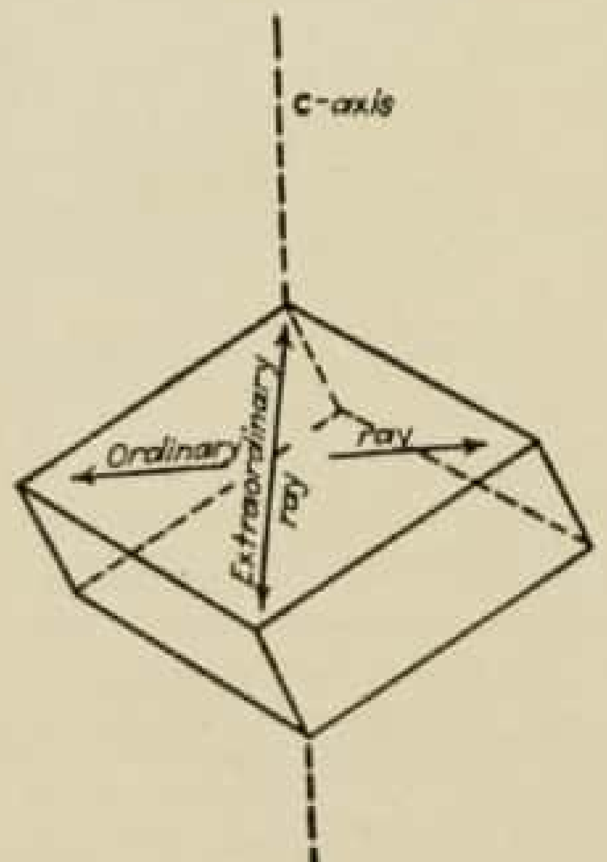


FIG. 53.—The extraordinary and ordinary rays in a calcite cleavage.

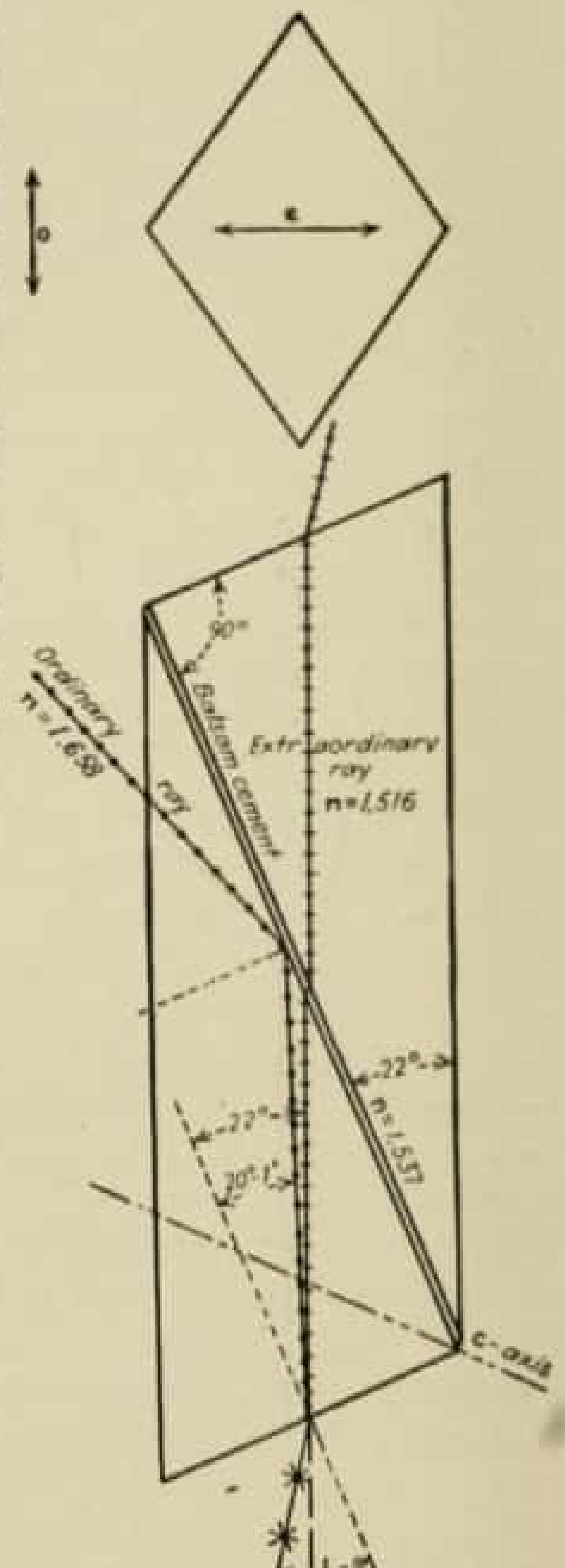


FIG. 54.—The polarization and deviation of light in a Nicol prism.

critical angle between the extraordinary ray and balsam, it passes on through the prism with little deviation.

The extraordinary ray is polarized with one plane of vibration; consequently, the light emerging from the prism and made up entirely of the extraordinary ray is plane polarized.

Interference between Crossed Nicols.—When two Nicol prisms are superimposed with their planes of vibration at right angles to each other, the nicols are said to be crossed. The polarizing microscope is normally adjusted with the Nicol prisms in this position, the plane of each nicol remaining fixed but the upper nicol movable either in or out of the tube of the microscope. Crossed nicols produce darkness when the stage is unoccupied or when it holds optically isotropic materials such as glass or opal or crystals of the isometric system of crystallization. Minerals crystallizing in crystal systems other than the isometric are anisotropic and in most positions produce interference colors between crossed nicols.

In Fig. 55 polarized light is shown passing through a mineral plate after leaving the lower nicol. Light strikes the lower surface of the mineral plate vibrating in one plane. On entering the plate, it is broken into two sets of rays. Both sets of rays are polarized, and light travels with different velocities along them. As a result, when the two sets of rays emerge on the upper side of the plate, one set has traveled farther than the other, and extraordinary rays will travel along the same direction as ordinary rays, both vibrating almost at right angles and having traveled different distances. Both travel along a straight line to the upper nicol and continue to vibrate at right angles.

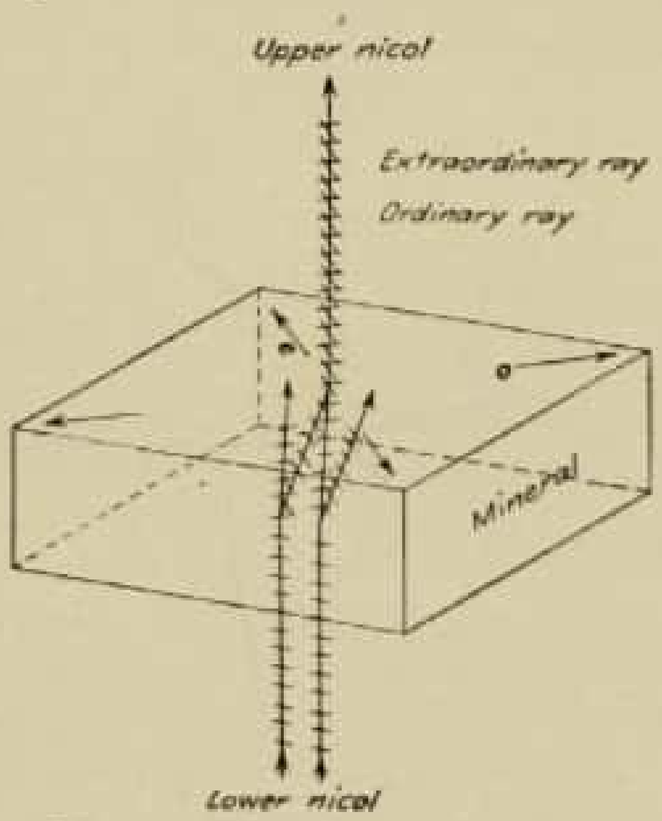


FIG. 55.—The vibration directions of the extraordinary and ordinary rays in an anisotropic mineral illuminated with polarized light.

The location of the planes of vibration is determined by the position of the mineral. If the position of the mineral plate on the stage is changed as shown in Fig. 56, the vibration planes of the emerging rays are also shifted.

After leaving the mineral plate, the two rays of the mineral, *e* and *o* in Fig. 57, continue to the analyzer. Here one of the rays *e* is broken into two components *eo′* and *ee′*, the ordinary ray *eo′* being refracted to the side of the nicol, the extraordinary ray *ee′* continuing through the upper half of the nicol. The separation of the rays follows the same principle already explained in the discussion of the Nicol prism. The other ray *o*, from the mineral, is also broken into two rays in the analyzer. One component *oo′* is reflected to the side, and the other *oe′* continues along the plane of the analyzer. As a result of this selection, two rays in the upper half of the analyzer *ee′* and *oe′* emerge as extraordinary rays

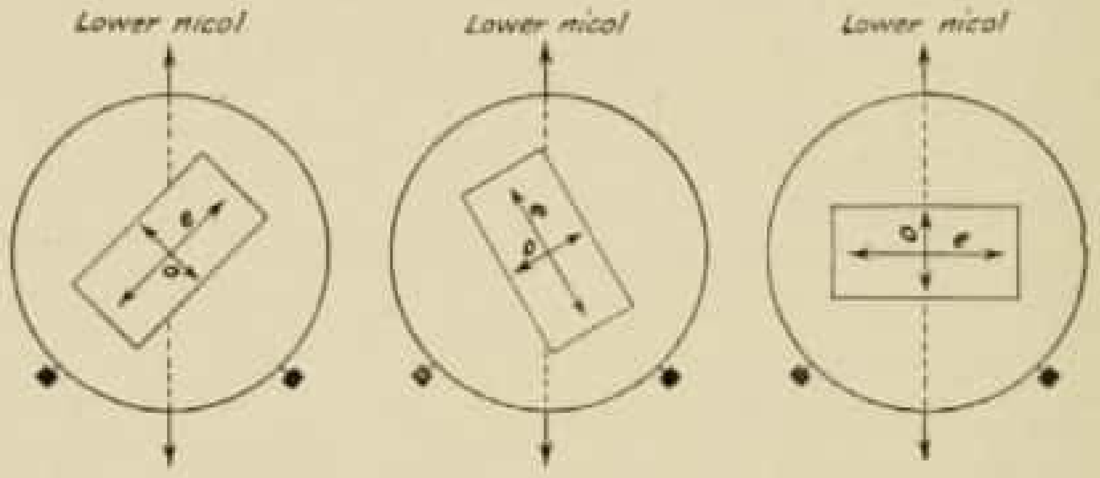


FIG. 56.—A mineral plate on the microscope stage showing several positions of the doubly refracting rays.

vibrating in the same plane. Although these two rays are vibrating in the same plane, each has traveled a different distance. In consequence, the two are in a position to interfere, and the resultant effect produced upon the eye is an interference color.

The interference color produced depends upon the nature of the light and the amount of retardation of one set of waves with respect to that of the other. The retardation can be determined and is expressed by the Greek letter Δ. The value of Δ is expressed in millimicrons (millionths of a millimeter = mμ), the same units used to measure the wave length of light.

The retardation may be changed through a wide range by (1) varying the thickness t of the mineral, (2) changing the orientation in such a way as to change the indices of refraction n_1 and n_2 of the two rays emerging from the mineral. This relationship may be expressed by the equation

$$\Delta = t(n_2 - n_1)$$

In the equation, t represents the thickness of the mineral expressed in millimeters, n_2 is the greater index of refraction, and n_1 is the lesser index of refraction for a particular orientation.

Phase Difference.—The two rays emerging from the mineral differ in phase, or in other words they have a phase difference P. This difference is equal to the retardation divided by the wave length:

$$P = \frac{\Delta}{\lambda}$$

Since it has just been shown that

$$\Delta = t(n_2 - n_1)$$

it follows that

$$P = \frac{t(n_2 - n_1)}{\lambda}$$

When the retardation is some whole multiple of a wave length ($n\lambda$), the waves emerging from the upper nicol become equal and opposite in phase. The resultant is then equal to zero, and the field produced is dark (Fig. 58).

When the retardation is $\left[\frac{(2n+1)}{2}\right]\lambda$, the components of the waves in the plane of the upper nicol are equal and on the same side of the line of transmission. The resultant wave is equal to the sum of the two components, and maximum intensity results (Fig. 59).

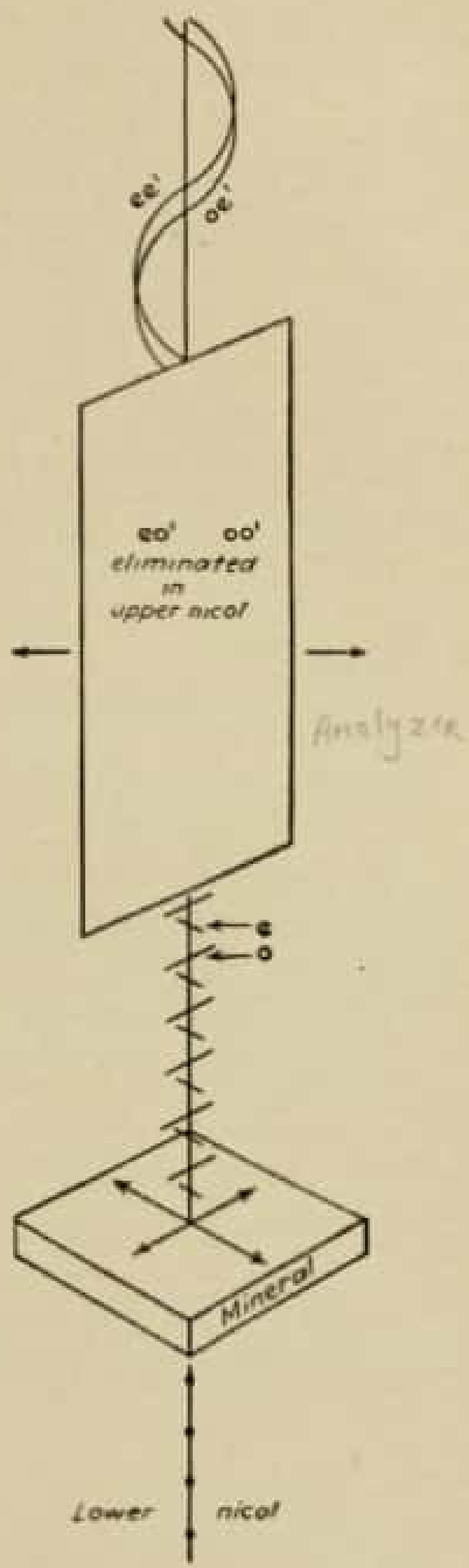


FIG. 57.—Sorting of rays by the upper nicol when the nicols are crossed.

Interference Colors.—If the mineral plate lies with the planes of vibration parallel and perpendicular to the planes of the two nicols, no light passes through the analyzing nicol, and the mineral is in a position of extinction. On the other hand, if

the mineral section is cut, and the light employed. The explanation of the relationship of these various factors involves many of the principles of optical mineralogy. It is desirable for the sake of simplicity to consider the variables one at a time.

If the thickness of a mineral plate between crossed nicols is changed, the orientation remaining the same, a change in

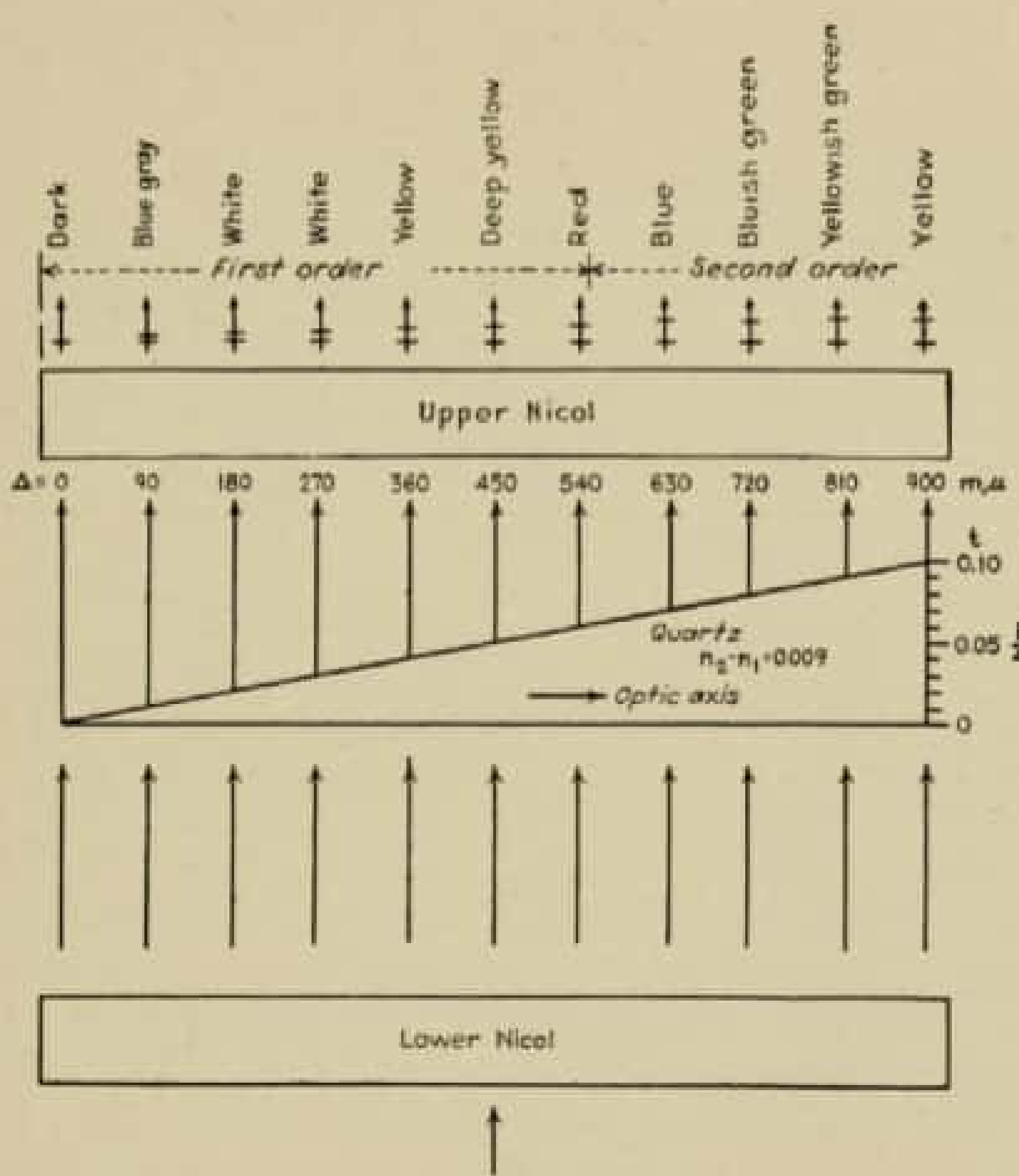


FIG. 60.—Interference colors due to a portion of a quartz wedge between crossed nicols with white light.

interference color ensues. One of the best ways to illustrate this phenomenon is by means of the quartz wedge that accompanies the polarizing microscope.

Figure 60 is a diagram illustrating a portion of a quartz wedge cut along the *c*-axis and varying in thickness from 0.0 to 0.10 mm. The wedge is placed between crossed nicols in a position at 45° to the planes of the nicols. In this position it becomes brilliantly illuminated with interference colors. The colors, how-

ever, gradually merge into each other and change as one observes different thicknesses along the wedge. Any one thickness, however, forms a uniform band of one color across the wedge. The quartz wedge should be placed on the stage of the microscope and moved back and forth in order to observe the full range of color due to varying thickness.

Each portion of the wedge is subject to the equation

$$\Delta = t(n_2 - n_1)$$

In this case, however, since the optic axis of the wedge remains parallel to the stage, $(n_2 - n_1)$ is fixed and equals 0.009. Consequently, the retardation Δ varies with the thickness t.

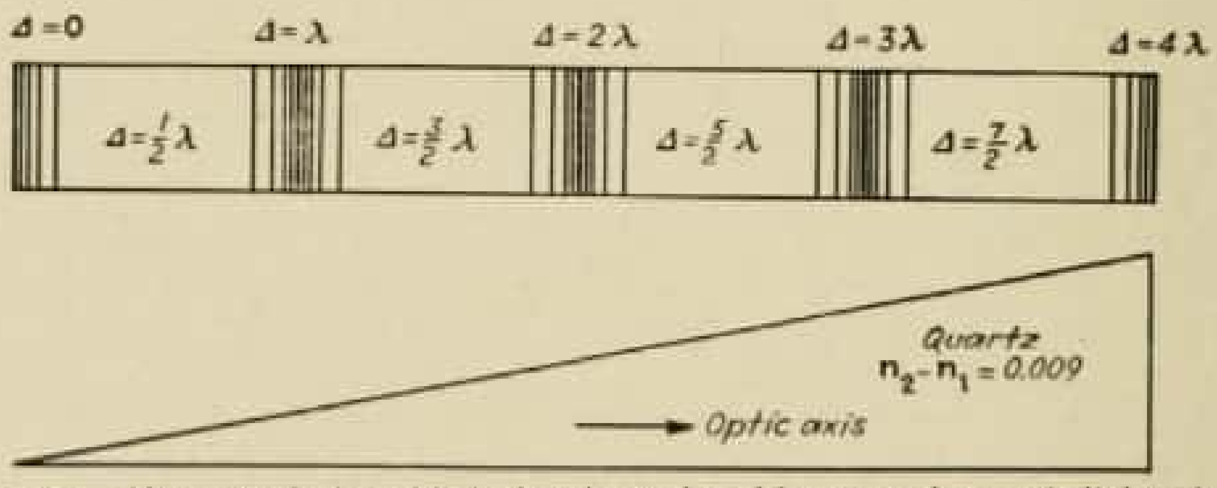


FIG. 61.—Alternate dark and light bands produced by monochromatic light with a quartz wedge between crossed nicols.

When t is zero, the retardation in any light is also zero, and the field of view is dark. In white light, when t increases, a definite sequence of colors ensues. Starting with gray and continuing through bluish gray, white, yellow, orange, in the order named, the colors become striking to the eye. In the thicker portion of the wedge, however, less contrast appears; and in wedges several times as thick the colors at the thick end become faint iridescent tints.

If the source of illumination is changed and monochromatic light is used in the system, a different effect is produced, as illustrated in Fig. 61. In this case, when the thickness reaches such a point that the retardation becomes equal to one wave length, the two monochromatic waves are equal and opposite in phase and nullify each other, causing darkness. As a result, dark bands will occur at all points where the retardation is a whole multiple of λ. Conversely, at odd multiples of $\frac{1}{2}\lambda$, maxi-

the plate is rotated to either side, the field of the upper nicol is no longer dark but becomes illuminated with interference

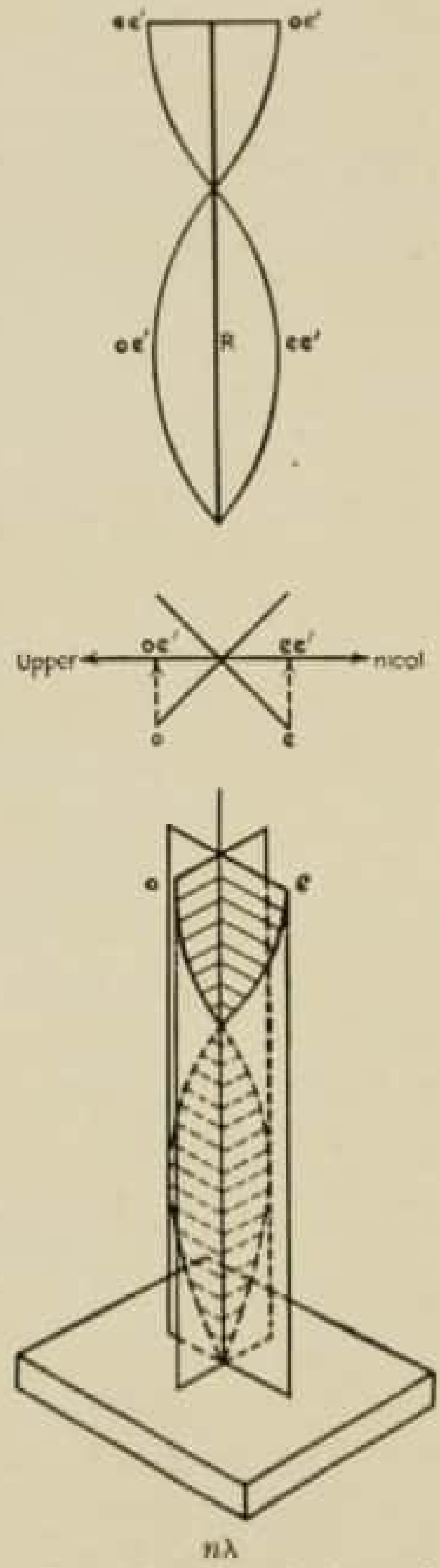


FIG. 58.—Resolution of waves in upper nicol for retardation of whole wave-length multiples.

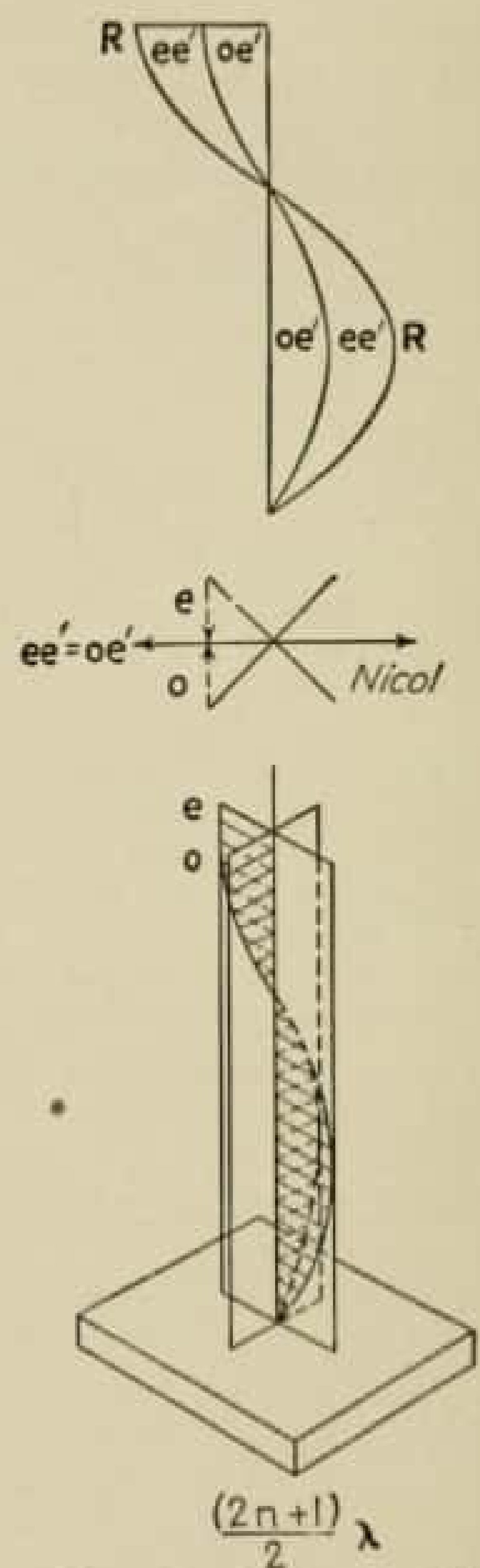


FIG. 59.—Resolution of waves in upper nicol for retardation of one-half wave-length odd multiples.

colors. The interference colors vary with the thickness of the mineral section, the nature of the mineral, the way in which

mum intensity will occur. Here the two waves are equal and in the same phase.

The interference colors due to white light are a subtraction of all the various wave lengths of the spectrum from white. The method by which the various interference colors are related to their monochromatic components is illustrated by Fig. 62.

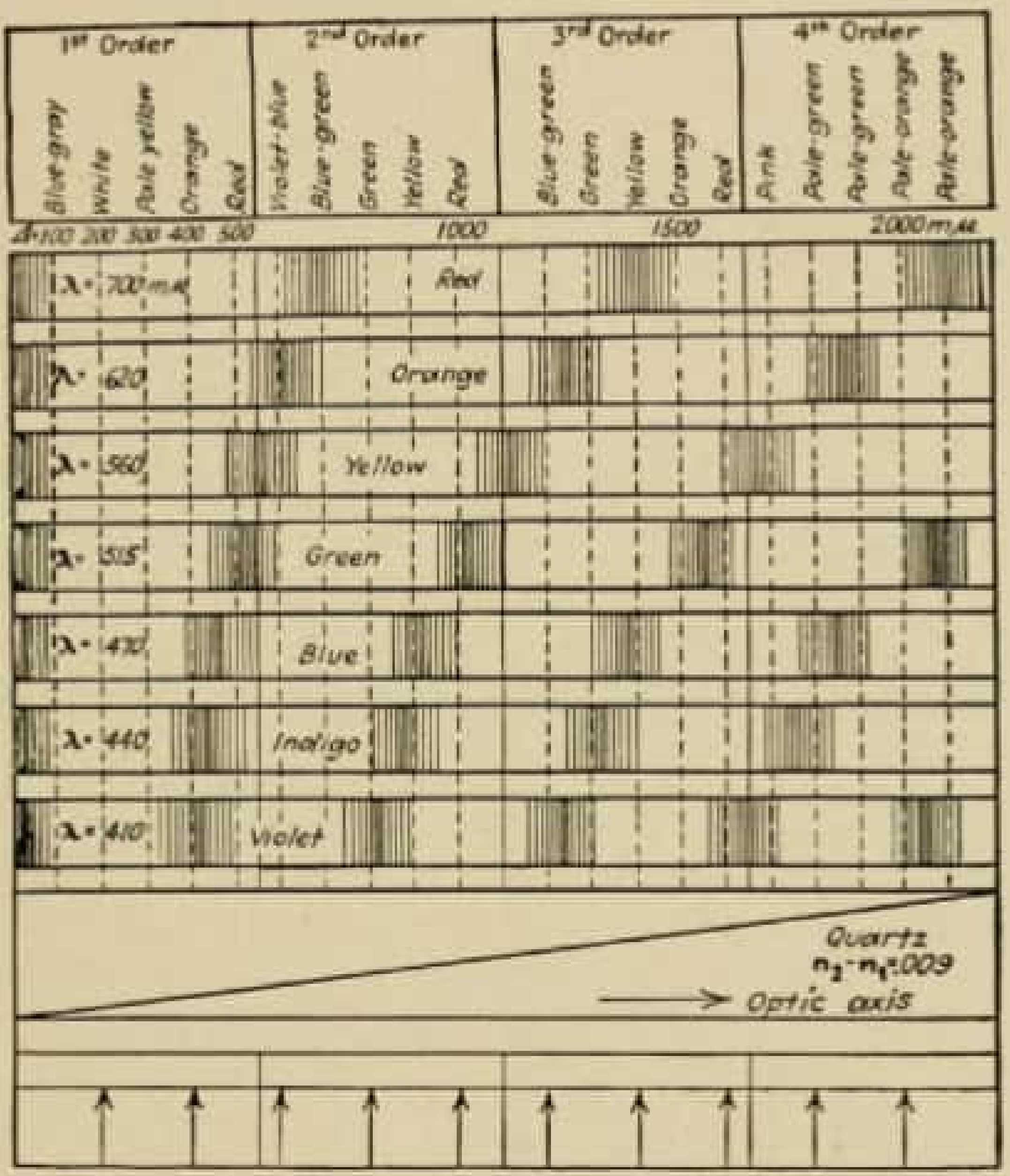


FIG. 62.—The relationship between interference colors due to monochromatic light and colors due to white light.

The various monochromatic beams, on passing through a wedge, produce dark bands at different thicknesses. Likewise, maximum intensity occurs at corresponding intermediate intervals. The difference between the wave lengths at the opposite end of the spectrum is such, however, that the first dark band for violet occurs almost in the first position of maximum intensity for red. For violet the band is approximately 410 mμ. Since the wave length for red is about 700 mμ, the maximum intensity for

red occurs at 350 mμ ($\frac{1}{2}\lambda$). When the thickness and double refraction are such that the retardation equals 410 mμ, no violet is present in the resultant interference color. The percentage of maximum intensity for red at the same time is about 83. Since the maximum intensity for red occurs at $\frac{1}{2}\lambda$ or 350 mμ, the percentage intensity at 410 mμ would be

$$\frac{2(\lambda r - \lambda v)}{\lambda r} \times 100 = \frac{2(700 - 410)}{700} \times 100 = 83 \text{ per cent}$$

If the wave lengths are known, it is possible to compute the percentage of any given monochromatic light present in an interference color of a given retardation.

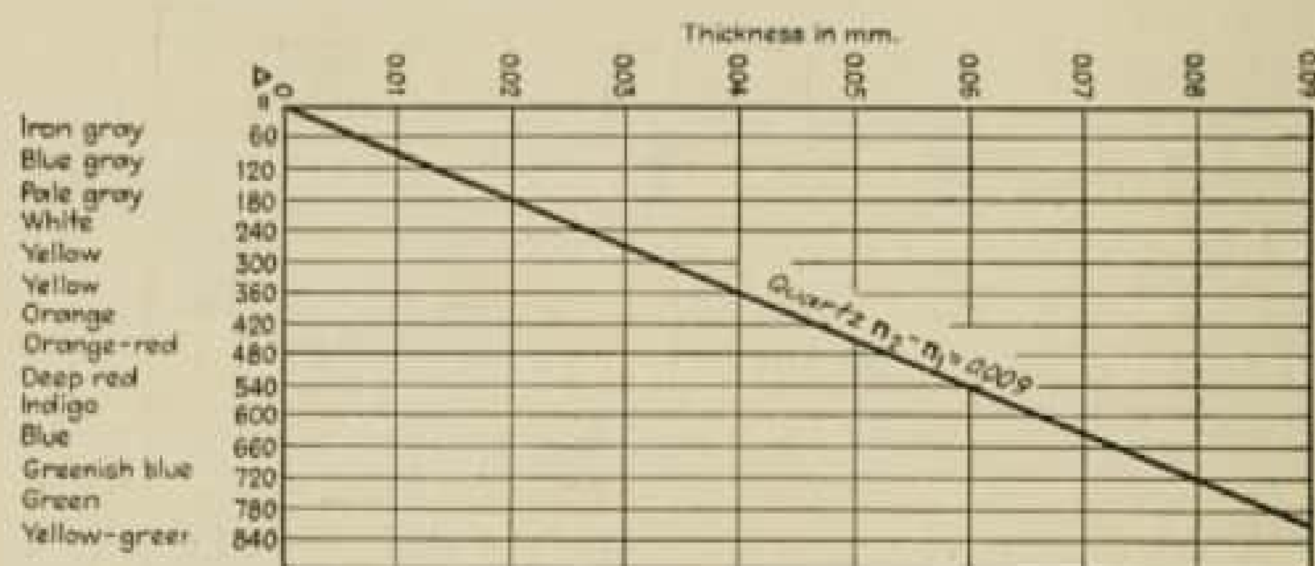


FIG. 63.—Variation in double refraction with thickness in the case of quartz.

Application of the Color Chart to the Study of Minerals.—The *interference color chart* is constantly employed in the study of minerals by means of polarized light. The maximum double refraction, or the greatest difference between n_2 and n_1, is approximately constant for a given mineral. If this constant is substituted in the equation $\Delta = t(n_2 - n_1)$, a straight-line curve is the result. In the case of quartz, for example,

$$(n_2 - n_1) = 0.009$$

If various thicknesses are assumed, as shown in Fig. 63, the corresponding retardation Δ may be determined directly. If the normal sequence of colors for a given retardation is known, it is possible either to predict the color of quartz of a given thickness or to tell the thickness of quartz having a given interference

color, provided the quartz is in such a position that $n_2 - n_1$ is a maximum.

This relationship not only is true for quartz but may be applied, with the exception of a few special instances, to all anisotropic minerals studied with the petrographic microscope. The color chart (facing page 163) gives the lines of maximum double refraction for the common minerals.

In the color chart interference colors with Δ less than 550 mμ are said to belong to the *first order*. Violet ($\Delta = 550$) belongs at the boundary of the first order. This is known as *sensitive violet*, since a small change either way produces a decided color difference. From violet $\Delta = 550$ to violet $\Delta = 1128$ the colors belong to the second order. From violet $\Delta = 1128$ to violet $\Delta = 1652$ they belong to the third order. Above the fourth order colors are not easily separated. The colors at the end of the first order and the beginning of the second are the most striking and brilliant. At the end of the fourth order they merge into each other, forming tints of green and pink tending toward grayish white. These colors are quite distinct from the blue gray, white, and yellowish white of the lower first order. Uncertainty concerning the order of a given color may be overcome by using a mica plate. The mica plate is cut with such thickness that it increases or decreases retardation of a section by about ¼λ (sodium light). Such an increase or decrease in the lower first or second orders produces a set of colors entirely different from that in the case of a similar change in higher orders. For example, in the case of first-order yellow $\Delta = 400$ mμ, an increase in Δ of 175 mμ will result in violet $\Delta = 575$ mμ, and a decrease of the same amount will produce white $\Delta = 225$ mμ. The same increase or decrease in retardation above the fourth order would produce little change perceptible to the eye.

Determination of Retardation with a Berek Compensator.—M. Berek (1913) described a rotary calcite compensator of simple mechanical construction. A calcite plate 0.1 mm. thick, cut normal to the optic axis, rests on a rotating axis in a metal holder similar to the frame usually used for the gypsum and mica plates. The frame is held fast in the accessory slot of the microscope by a spring. The rotation of the compensator plate is registered on a graduated drum attached to the axis of rotation. The drum

is graduated with a vernier reading to tenths and may be calibrated in degrees.

The plate in the compensator is held in a small ring that may be easily removed, and a plate of different thickness may be substituted. The range of the plate ordinarily employed covers retardations from zero to the fourth order.

The axis of rotation of the compensator is arranged diagonally to the polarization planes of the two nicols. If the planes of the nicols are north-south and east-west, the tube slot holding the compensator will be northwest-southeast. The compensator is

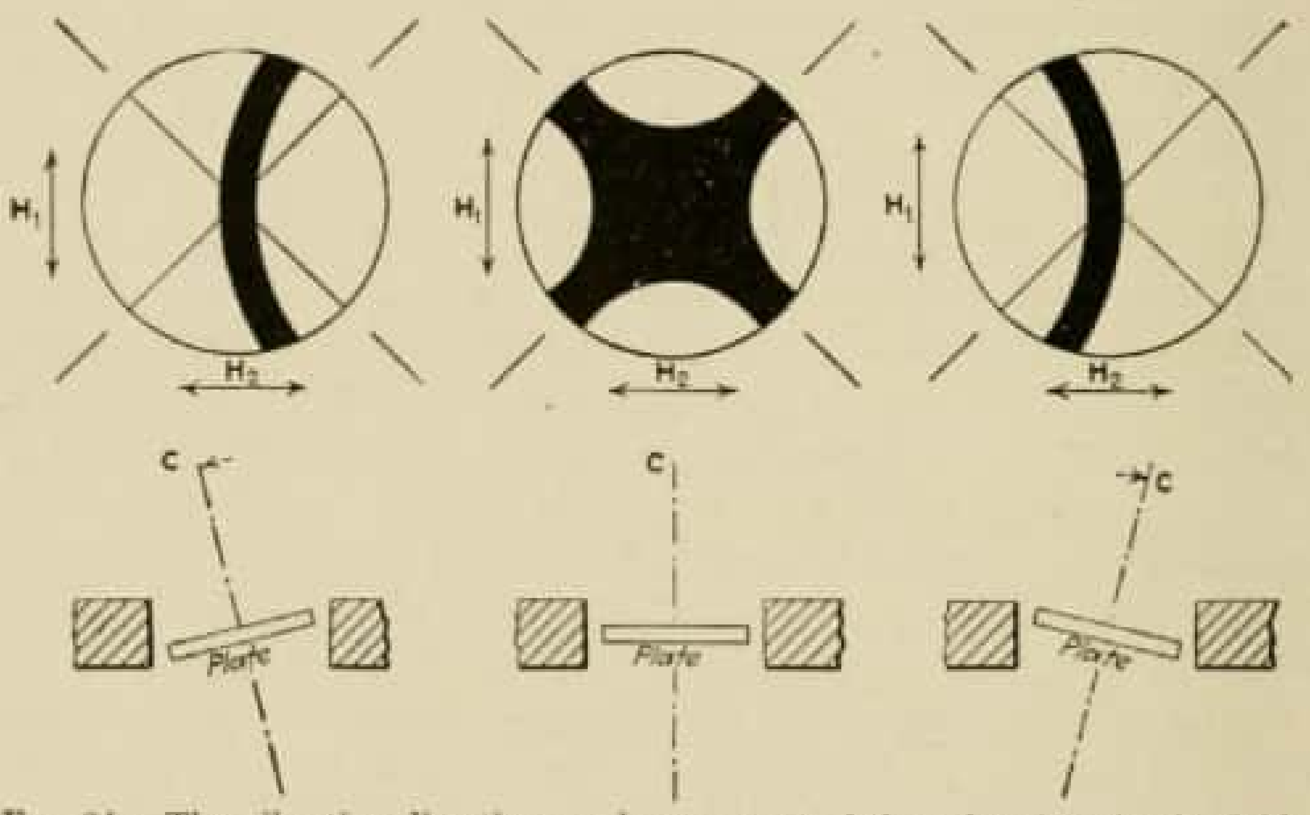


FIG. 64.—The vibration directions and movement of the color rings in the field of the ocular when using the Berek compensator.

marked with two arrows: H_1, parallel to the axis of rotation or along the accessory slot, is the slow-ray vibration direction; H_2, at right angles to the axis of rotation, indicates the trace of the projection of the plane containing the inclined *c*-axis of calcite and marks the fast-ray vibration direction.

The compensator is first set with the plate horizontal within the frame and inserted. Between crossed nicols a large dark cross will appear in the field. When this cross coincides with the crosshairs of the microscope, the compensator is in the zero position (see Fig. 64). If the compensator drum is then turned either to the left or to the right, the various orders of interference colors appear in the field in a sequence corresponding to the order of the quartz wedge.

The compensator may be used to determine the retardation of a mineral grain between crossed nicols as follows: The grain in question is moved to the center of the field and placed in the 45° position with the slow-ray vibration direction of the mineral parallel to H_2 of the compensator. The compensator is then inserted and rotated first to the right and then to the left, stopping in each case when the interference color of the mineral has been completely reduced to extinction. The measured difference between the opposite readings is divided by two and the value inserted in a simple formula supplied by the makers of the

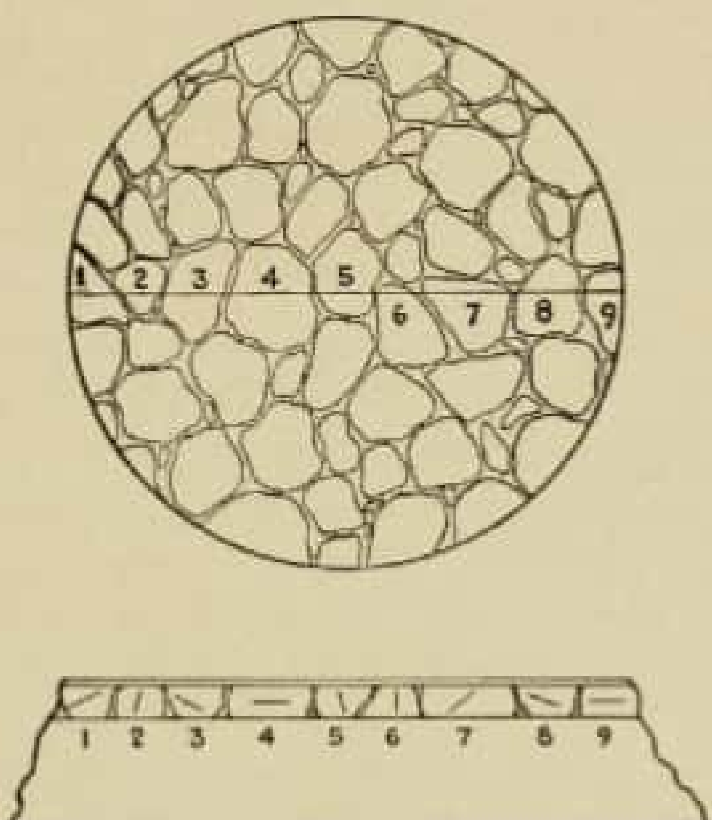


Fig. 65.—Determination of thickness of section in quartzite.

instrument. Solution of the formula gives the correct retardation for the mineral grain.

A view of the Berek compensator is shown in Fig. 17. Figure 64 indicates the views obtained in the microscope field with the compensator plate horizontal and rotated either to the right or to the left. The vertical sections in the lower part of Fig. 64 indicate the inclination of the *c*-axis, and the upper diagrams represent corresponding microscope fields. With monochromatic light, light and dark bands are produced on either side of a central cross. With white light, the bands on either side of the dark cross indicating the zero position are colored.

When the compensator is inserted above a doubly refracting crystal in a thin section, the dark cross disappears. As the plate

is rotated, however, the interference colors are changed until complete compensation occurs as mentioned above.

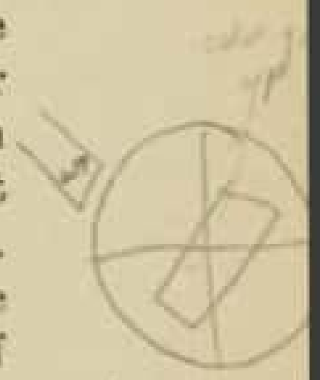
Determination of Thickness of Section.—Let us suppose that Fig. 65 represents a thin section containing numerous small quartz grains in random orientations. For purposes of illustration we shall refer to grains 1 to 9 inclusive along the horizontal crosshair in the field of the microscope. These grains are oriented with their optic axes lying in the positions shown in the sectional view. Most are inclined; occasionally a few are vertical and a few are horizontal. The horizontal axes are in the correct position to provide a maximum value of $(n_2 - n_1)$. Since all are of uniform thickness, the grains with horizontal axes will show the highest order of interference color, which is likewise the interference color with maximum retardation. In any section of uniform thickness that has a large number of grains, as in the case illustrated, the grains giving the highest order interference color as observed by means of the color chart will be grains in a position to exhibit the maximum $(n_2 - n_1)$. In the case at hand, grain 4 is in the correct position. If grain 4 should show an interference color of straw yellow, the thickness of the section as determined by the color chart would be 0.03 mm. Other interference colors will be shown in the thin section, but only those with an approximately horizontal position will be as high in the first order as straw yellow.

In any thin section, if sufficient grains of a known mineral are present in random orientation and the highest order of interference color can be determined, it is possible to ascertain the thickness of section by reference to the color chart. It is also possible to reverse the process if the thickness is known and determine the double refraction of an unknown mineral. Likewise, in a slide containing two or more minerals, one of which is known, it is possible to determine the thickness of the section from the known mineral and determine the double refraction of the unknown minerals from the determined thickness and the observed interference colors. These considerations are extremely useful in studying minerals with the polarizing microscope.

Direction of the Vibration of Slow or Fast Rays.—It is frequently important to ascertain the planes of vibration of the two rays vibrating at right angles in an anisotropic mineral grain. The two rays have different indices of refraction, the one with

the greater index being the slow ray and the one with the lesser index, the fast ray. The determination of the fast- and slow-ray directions is accomplished between crossed nicols, the location of the two rays being established by observing the position of extinction. When the mineral becomes dark, the vibration directions of the two rays are parallel to the planes of vibration of the Nicol prisms. Since the planes of vibration of the nicols are parallel to the crosshairs in the ocular, the vibration planes in the mineral will also be parallel to the crosshairs when in the extinction position.

A mica plate or a gypsum plate is used to tell which of the two rays is fast and which is slow. When the positions of the vibration directions of the rays are ascertained, the mineral is turned from extinction to the position of maximum interference. Next, either the gypsum or the mica plate is inserted in the tube of the microscope with the slow-ray vibration direction parallel to one of the vibration directions of the mineral. If the order of color increases, the parallel direction is the slow-ray vibration direction of the mineral. If it decreases, the direction represents the fast ray. One direction being known, the other is the opposite. The mica plate is usually used for minerals with weak double refraction, and the gypsum plate is employed in the case of stronger double refraction. When the mineral has very strong double refraction, a quartz wedge may be used. Since the quartz wedge varies in retardation from zero to the fourth order, a variety of colors will be produced, the color at a particular part of the wedge depending upon the thickness. When the slow ray coincides with the slow-ray direction in the mineral, a corresponding reinforcement in retardation will occur. Thus the color of the mineral will suddenly change to a color of higher order, dependent upon the portion of the wedge superimposed. When the slow-ray direction in the wedge is opposed to the slow-ray direction in the mineral, subtraction occurs.



Extinction.—When a mineral plate or grain or a portion of a doubly refracting crystal is dark between crossed nicols, it is said to lie in the position of extinction. Frequently minerals have prominent cleavage lines or crystal boundaries that enable one definitely to locate the angle at which extinction occurs with respect to the crystallographic axes. In the absence of a reference line, the extinction angle cannot be determined.

Parallel Extinction.—Frequently minerals have a single plane of cleavage. The traces of the cleavage planes appear in thin sections as irregularly spaced parallel lines. If the mineral becomes dark between crossed nicols, with the cleavage parallel to the vibration directions of the two nicols, the extinction is said to be parallel.

A number of minerals crystallize in such a way that sections are elongated, square, or rectangular. Square or rectangular cleavage patterns may also be observed. If these minerals become dark between crossed nicols, with the cleavage directions parallel to the vibration planes of the nicols, they are said to have parallel extinction.

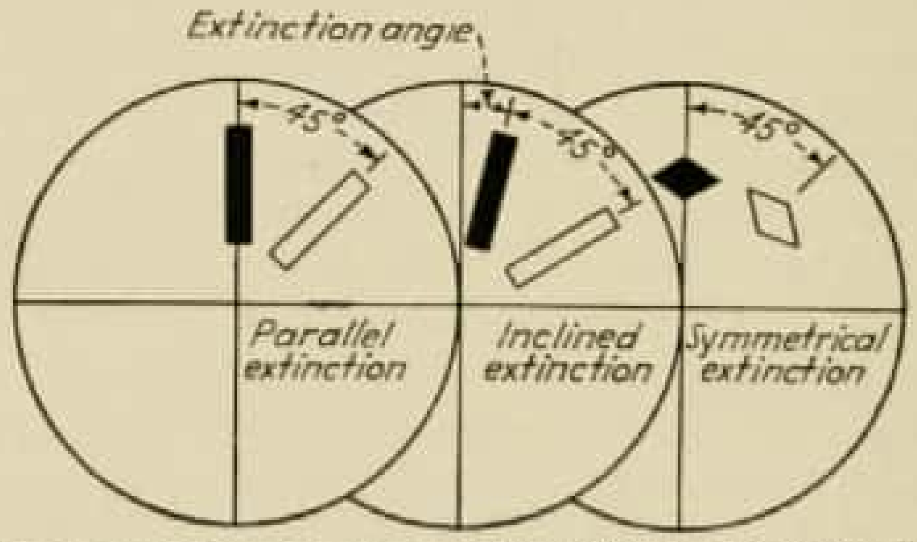


FIG. 66.—Relative positions of greatest and least illumination in parallel, inclined, and symmetrical extinction as observed between crossed nicols.

Inclined or Oblique Extinction.—Many minerals extinguish between crossed nicols when cleavages or crystal boundaries lie at oblique angles to the planes of vibration of the two nicols. These are said to have inclined extinction.

In this case it is necessary to know the position of either the fast-ray vibration direction or the slow-ray vibration direction in the mineral grain. The extinction angle is usually determined in terms of the slower of the two rays, or the one having the greater index of refraction. The nature of the two rays is determined with one of the accessory plates of the microscope.

Several different angles of extinction are usually observed for the same mineral in a given section, as illustrated in Fig. 67. The maximum reading on the slow-ray vibration direction with the plane of vibration of the analyzer is a convenient value to determine. In the case of observation with the microscope, the

stage is rotated until the mineral lies in a position of extinction. The upper nicol is then pushed to one side, and the angle between the vertical crosshair (parallel to one of the nicols) and the cleavage line or crystal boundary is determined by readings on the graduated stage of the microscope. The nicols are then crossed again and the crystal turned to the extinction position, the angle being measured. Next, the direction of vibration of the slow

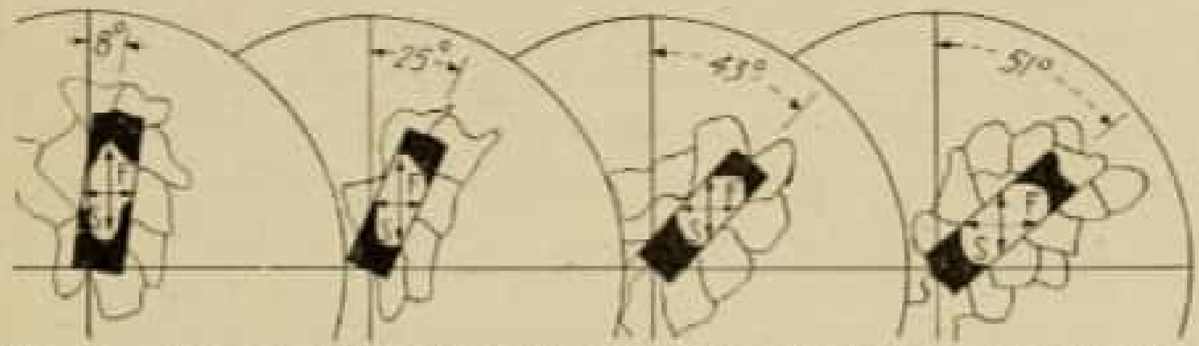


Fig. 67.—Diagram illustrating various positions of an elongated mineral with a maximum extinction angle of 51° on the slow ray as it might appear in thin section.

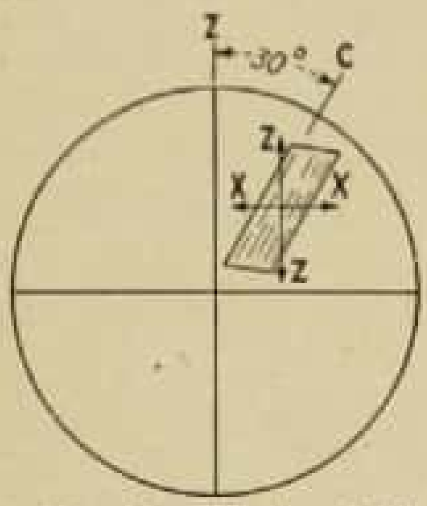


Fig. 68.—Hornblende of Fig. 264*b* in the position of maximum extinction. between crossed nicols.

C ∧ Z = −30°.

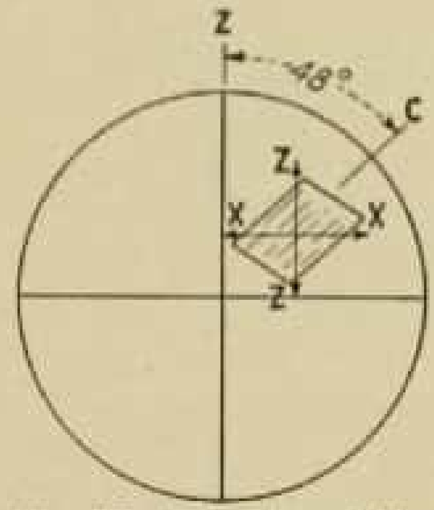


Fig. 69.—Hedenbergite of Fig. 245*b* between crossed nicols in the position of maximum extinction.

C ∧ Z = −48°.

ray is verified by using an accessory plate. A series of readings should be repeated with different crystals until it seems certain that the largest angle for a particular mineral has been found. When the angle is determined, it is necessary to refer to a description of the optical directions in the crystal in order to ascertain the proper reference plane for the extinction angle.

The mineral descriptions in Part II of this text include the angles of extinction. The angle between Z and the *c*-axis of a crystal is frequently recorded. Since Z is a slow-ray direction and prominent cleavages or crystal boundaries are often referred to the *c*-axis, it is usually possible to interpret the extinction from

the orientation diagram. Figures 68 and 69 furnish illustrations of such interpretations.

Symmetrical Extinction.—A number of minerals form cleavage patterns or crystals with rhombic cross sections. In many instances these become dark between crossed nicols when the planes of vibration of the nicols are parallel to the diagonals of the rhombic patterns. Extinction of this type is described as symmetrical. Several minerals forming crystals with square outlines may also yield symmetrical extinction.

Elongation.—Occasionally crystal grains develop with an elongated habit and straight edges. These may have a lathlike shape under the microscope, may resemble small needles, may occur in long crystals, or may show several other shapes of similar development.

When such crystals are anisotropic, it is possible to determine the fast- and slow-ray vibration directions with one of the marked accessory plates. In case the vibration direction of the slow ray of the crystal is parallel to the long direction, the mineral is said to have *positive elongation.* When the vibration direction of the slow ray lies across the crystal in the short direction, the mineral has *negative elongation*. These two terms may be stated briefly as *length-slow* and *length-fast*, length-slow indicating that the vibration direction of the slow ray is parallel to the length of the crystal, and length-fast indicating the parallelism of the vibration direction of the fast ray.

Anomalous Interference.—Occasionally minerals normally assumed to be isotropic become anisotropic and give interference effects between crossed nicols. The abnormal production of interference colors often of a low order is called *anomalous.* Figure 121 represents a thin section of garnet that exhibits symmetrically arranged bands of interference colors photographed between crossed nicols. X-ray studies show that the same garnet is still isometric in crystallization, so the colors are truly anomalous.

Interference colors and structural patterns may be produced by strain in the crystals. According to Crookes, the great Cullinan diamond, measuring almost 4 in. across, exhibited pronounced anisotropism due to strain.

Idocrase in thin section often shows an unusual sequence of interference colors, Berlin blue predominating. Although this

mineral is tetragonal and normally doubly refracting, the interference colors do not follow the color chart and are anomalous. Clinozoisite, zoisite, brucite, and some varieties of chlorite furnish other examples of anisotropic minerals that yield anomalous interference colors.

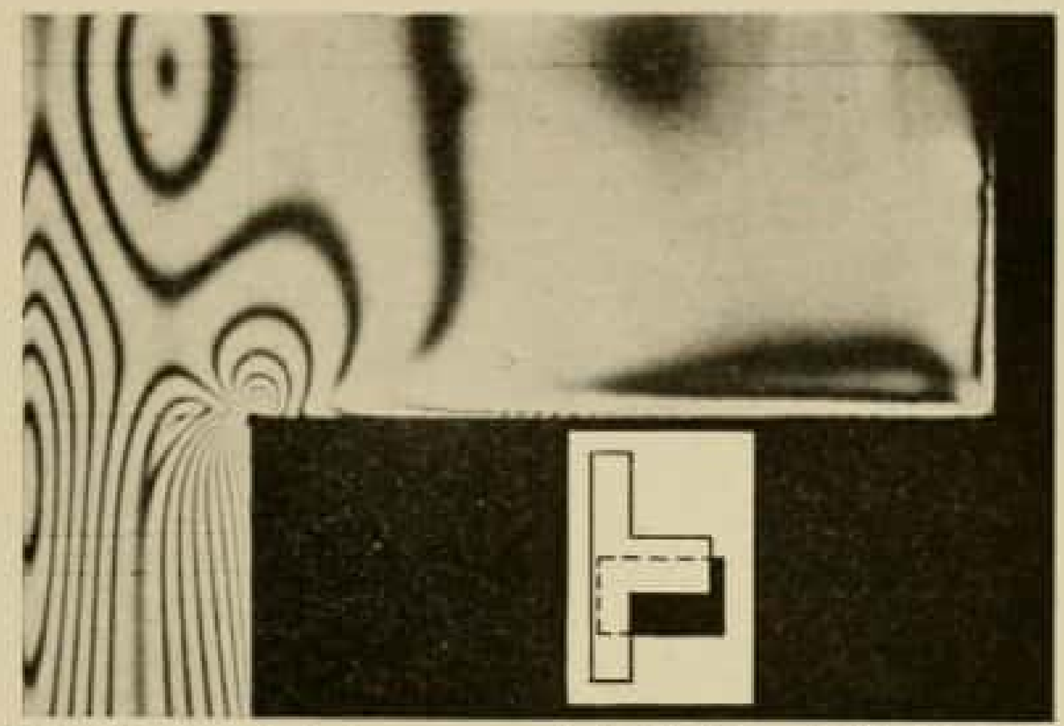


FIG. 70.—Photograph between crossed nicols of equal interference areas in strained bakelite cut in the form of a structural T and placed under pressure. (*Courtesy of Photo Elastic Laboratory, Department of Civil Engineering, Columbia University; photograph by Raymond D. Mindlin.*)

Equal interference areas are frequently produced in isotropic bakelite through strain. In Fig. 70 a portion of a small bakelite frame cut in the form of a T is shown between crossed nicols. The T would have a shape illustrated by the insert, the portion photographed being outlined by the dotted lines. The photograph was obtained by utilizing monochromatic green (5461 A.U.) in the mercury spectrum.

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CHAPTER VI

CONVERGENT POLARIZED LIGHT

General Statement.—The lens combination used in the microscope for obtaining interference figures is usually described as conoscopic. The usual arrangement produces interference figures visible in the field of the ocular. Such figures are particularly useful for determining the optical directions in crystals. Their interpretation involves the principles outlined in the preceding chapter on polarized light, combined with an understanding of the crystallization of minerals.

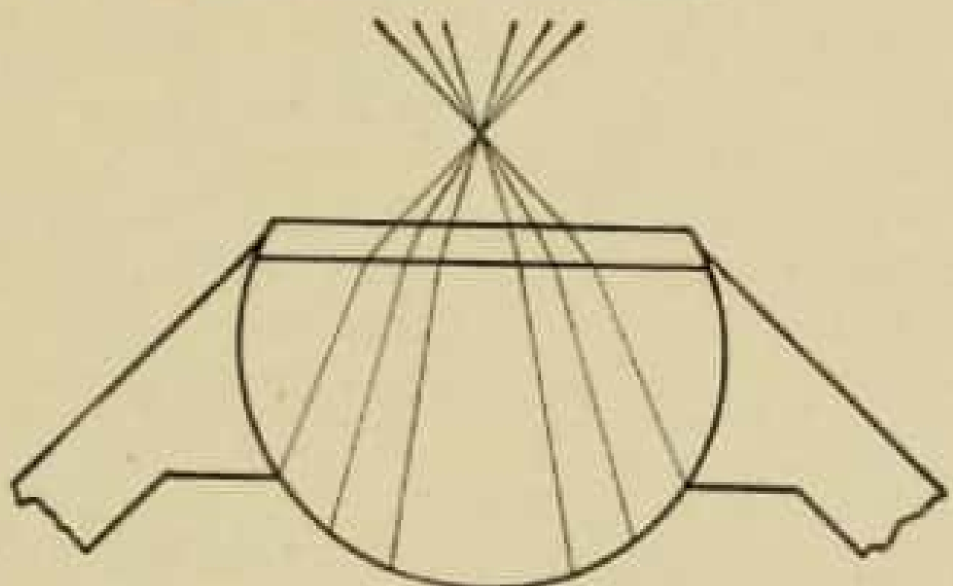


FIG. 71.—Convergent light produced by the front lens of the condenser.

In obtaining interference figures of small crystals, it is necessary to exercise particular care to have all of the elements in the optical train exactly aligned and properly centered. It is best to use a moderately high magnification, preferably a 4-mm. objective, although an 8-mm. objective is sometimes satisfactory and may be more easily manipulated. The auxiliary condenser should be inserted across the axis of the microscope below the stage. The front lens of the condenser throws a concentrated convergent beam against the mineral plate (Fig. 71). Some microscopes are also provided with a diaphragm between the polarizer and the lower component of the condenser. The diaphragm limits the field of view and helps to improve the outer portion of the interference figure. A Bertrand lens is inserted in

the tube of the microscope above the analyzer. This lens brings the image of the interference figure into focus on the focal spot of the ocular. The figure then becomes visible to the observer through the ocular. Good figures of small size can be obtained by removing the ocular and not using the Bertrand lens. A black disc with a small hole in the center, or any one of several appliances designed for this purpose, may be used to replace the ocular when an interference figure is obtained without the Bertrand lens.

Two types of interference figures are given by anisotropic minerals: uniaxial and biaxial. Minerals crystallizing in the hexagonal and tetragonal systems are uniaxial; those crystallizing in the orthorhombic, monoclinic, and triclinic systems are biaxial. The difference between uniaxial and biaxial minerals is fundamental and is due to the arrangement of the atoms set up in crystallization. Occasionally biaxial crystals have such a small axial angle as to appear uniaxial, and conversely on certain occasions normally uniaxial crystals may become biaxial because of strain. Such variations should be examined with caution when encountered, yet they need not disturb the student's confidence in the interpretation that tetragonal or hexagonal crystals are uniaxial, whereas monoclinic, orthorhombic, and triclinic crystals are biaxial.

Formation of Interference Figures.—Convergent light passing through a crystal plate causes variation in retardation between crossed nicols. This variation in retardation has many points in common with the variation in retardation obtained with the quartz wedge, as described in the discussion of parallel polarized light. The use of the quartz plate instead of a wedge and of convergent polarized light instead of parallel polarized light produces interference colors dependent upon the convergence of the beam. The varying angle of illumination of the oblique rays results in varying values of n_2 and n_1 for a doubly refracting mineral. Varying values of n_2 and n_1, in turn, cause varying retardation.

When a quartz plate is being examined the most striking interference effect occurs with the optic axis of the plate at right angles to the microscope stage. The same fundamental considerations that have been demonstrated to hold true in the case of the wedge also apply to the plate. Here, however, the thickness

remains constant, and the double refraction $(n_2 - n_1)$ varies with the retardation, depending upon the direction. The angle of incidence on the quartz plate due to the convergent beam employed varies from 0 at the center of the field to a maximum on either edge. As a result, the difference $(n_2 - n_1)$ also changes from 0, at the center where the incident beam is parallel to the

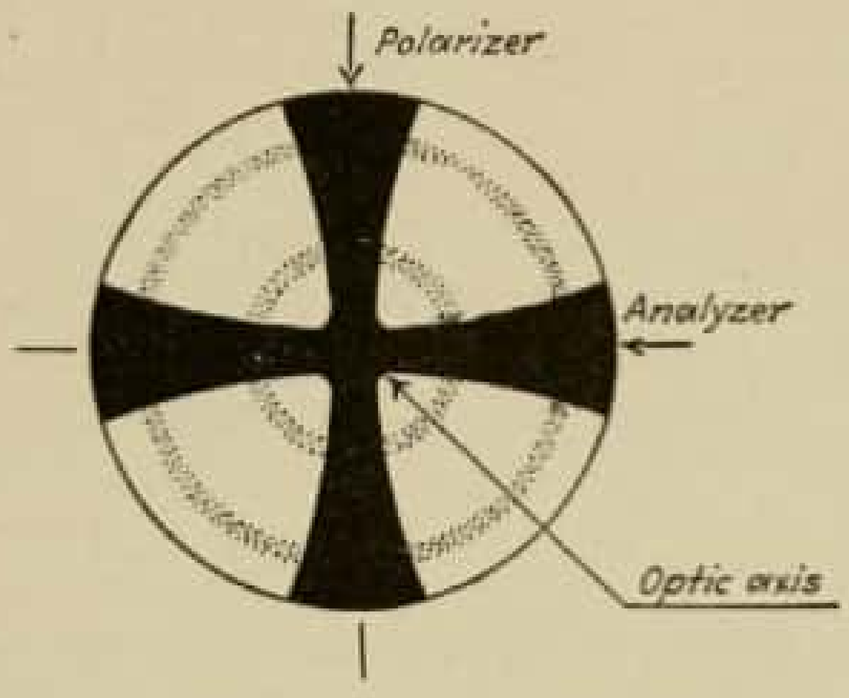


FIG. 72.—A uniaxial interference figure looking down on an optic axis.

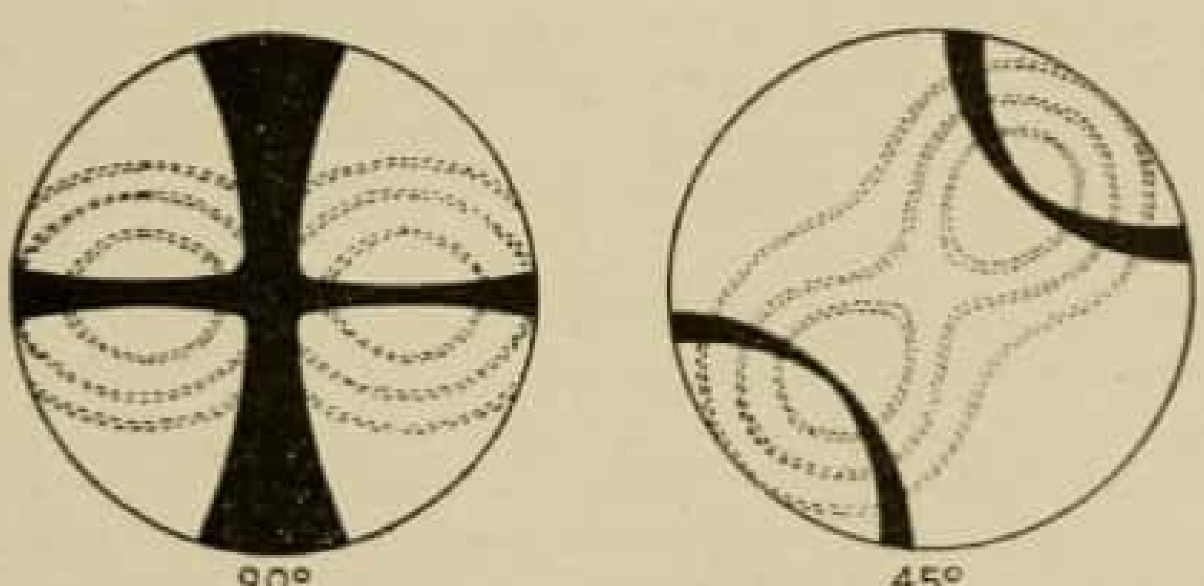


FIG. 73.—A biaxial interference figure in 90° and 45° positions.

optic axis, to considerably greater values at the edge of the field. Darkness or total extinction occurs at the center of the field and where the vibration directions of the inserted plate are parallel to the vibration directions of the nicols, resulting in a black cross for quartz. The explanation lies in the fact that convergent light strikes the surface of a mineral plate not only along a straight line, as in a section of a quartz wedge illuminated by parallel polarized light, but also radially around the center. Consequently, vibration directions will be arranged tangentially

and radially throughout 360° of rotation. As a result, vibration directions of the extraordinary and ordinary rays from the plate will be parallel to the vibration planes of the nicols in certain directions. The two directions are directions of extinction and in general uniaxial minerals form dark cross arms at 90° (Fig. 72). In biaxial minerals the positions of extinction show greater variation, and the interference figure is no longer a simple cross but changes as shown in Fig. 73. The different orders of color in the field are arranged in concentric circles around the center of the cross. Other factors remaining the same, the number of color bands observed in a particular field is dependent upon the thickness of the plate and the double refraction of the mineral.

Monochromatic light produces alternate dark and light bands in interference figures. The dark bands correspond to retardations of $n\lambda$, and the intermediate maximum colored bands correspond to a retardation of $\frac{(2n+1)\lambda}{2}$. The relationship is similar to that which results when monochromatic light is passed through a quartz wedge. The colors in interference figures produced by white light are actually a combination of the different monochromatic wave lengths due to the varying oblique angle of illumination. This is analogous to the interference color chart where white light results as a summation of the various monochromatic wave lengths due to variation in thickness.

Uniaxial Interference Figures.—Hexagonal and tetragonal minerals yield the characteristic axial cross of a uniaxial interference figure when viewed in the direction of the optic axis. If the optic axis of the mineral (the same in direction as the crystallographic *c*-axis) coincides with that of the microscope, the uniaxial figure will be centered with the two arms crossing at the intersection of the crosshairs in the microscope.

However, if the optic axis is inclined to the axis of the microscope, the point of intersection of the cross arms will fall away from the intersection of the crosshairs. It frequently falls outside the field of the microscope. If the center of the axial cross does not coincide with the center of the field, the point of intersection of the arms will move around the crosshair intersection when the stage is rotated, describing a circle and returning to its original position after rotating 360°. The intersection of the cross arms marks the point of emergence of the optic axis, and

its deviation from the center of the field is a measure of the angle between the optic axis and the axis of the microscope.

Although uniaxial figures are frequently eccentric in position, the cross arms remain parallel to the planes of vibration of the nicols. Because of this fact the arms sweep the field first from

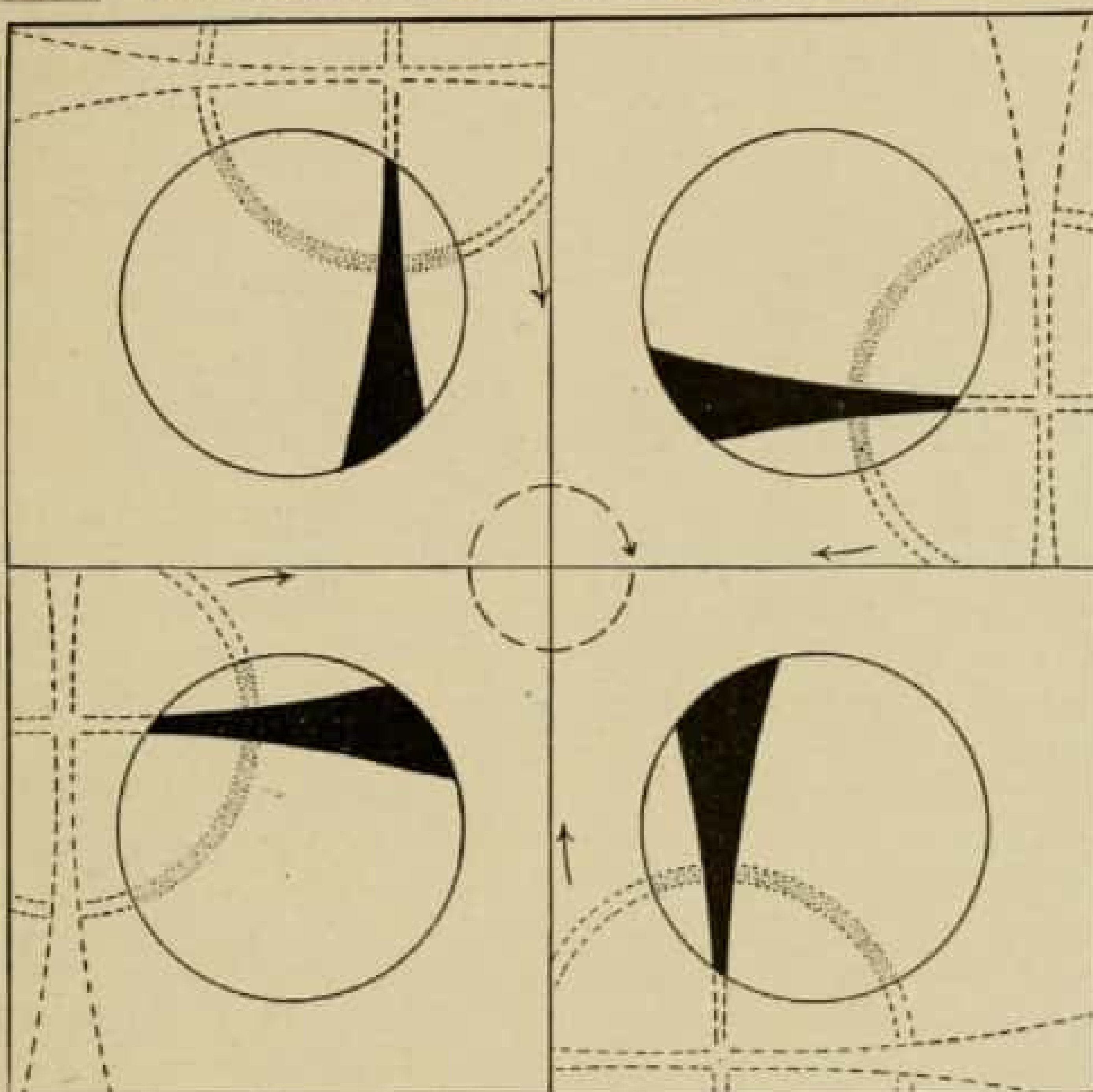


FIG. 74.—Uniaxial interference figure in eccentric positions. Dotted lines indicate the movement of the figure around the field of the microscope as the stage is rotated.

one side, then from another as the stage is rotated. It is important to note whether the arms remain parallel to the crosshairs, since arms in certain biaxial figures also cross the field. The latter are curved or crescent shaped, however, and swing across the field rather than sweep parallel to the nicols. Several eccentric positions of a uniaxial figure are shown in Fig. 74.

The number of color bands in uniaxial interference figures varies with the thickness of the section and the double refrac-

tion of the mineral. For example, thick sections of a uniaxial mineral may give a number of orders of colors, whereas a thin section of the same mineral may not yield bands of color above the first order. On the other hand, if two plates are made of different minerals, both of identical orientation and having the same thickness, the mineral with the greater double refraction will develop the greater number of color bands. The relation between uniaxial figures due to mineral plates of the same thickness but differing in double refraction is shown in Fig. 75.

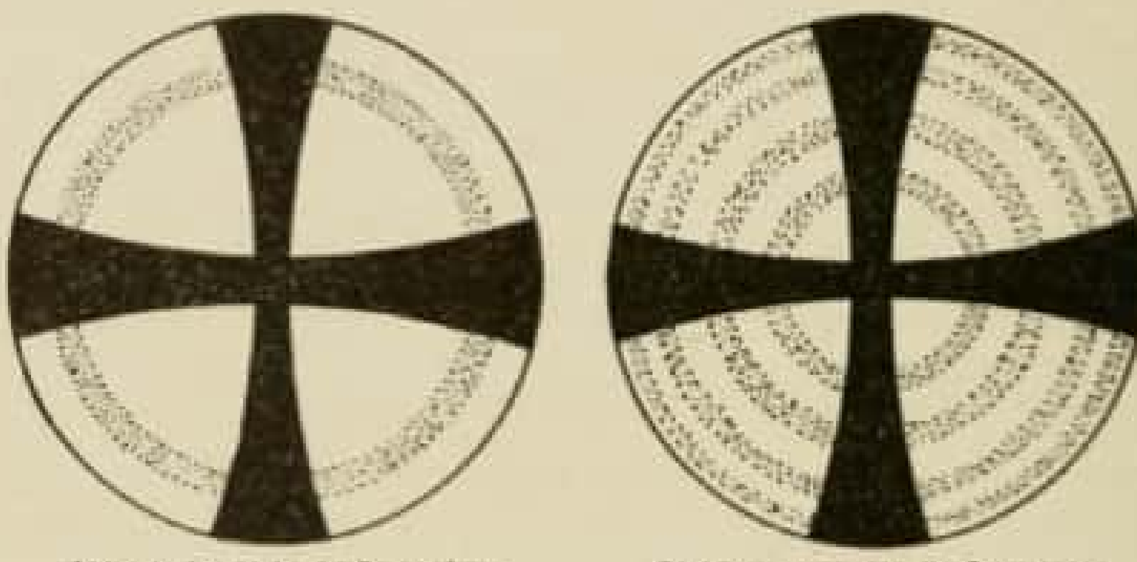


FIG. 75.—The comparative effect of strong and weak double refraction on the color bands of a uniaxial interference figure.

Vibration Directions in Uniaxial Crystals.—Convergent polarized light on emerging from a uniaxial mineral in the direction of the optic axis has specific vibration directions. One significant ray vibrates parallel to a plane that includes the *c*-axis of the crystal; another vibrates parallel to a plane at right angles. The two are refracted differently and consequently travel different distances in passing through the mineral plate.

In the upper nicol, resolution occurs into the plane of vibration of the nicol. When the rays vibrate parallel to the nicols, resolution is zero, and darkness occurs—hence the axial cross. At the 45° position of stage rotation the greatest intensity occurs, and the interference colors are most brilliant.

When two sets of rays are formed by the passage of light through a uniaxial crystal, one set travels with uniform velocity in all directions and is known as the *ordinary ray;* the other varies in velocity with direction and is called the *extraordinary ray.* If light were to radiate out from the center of a solid mass of such an anisotropic medium, at a given instant the wave front

of the ordinary ray would be spherical, whereas the wave front of the extraordinary ray would be ellipsoidal. Any section of the wave front produced by the ordinary ray would therefore be

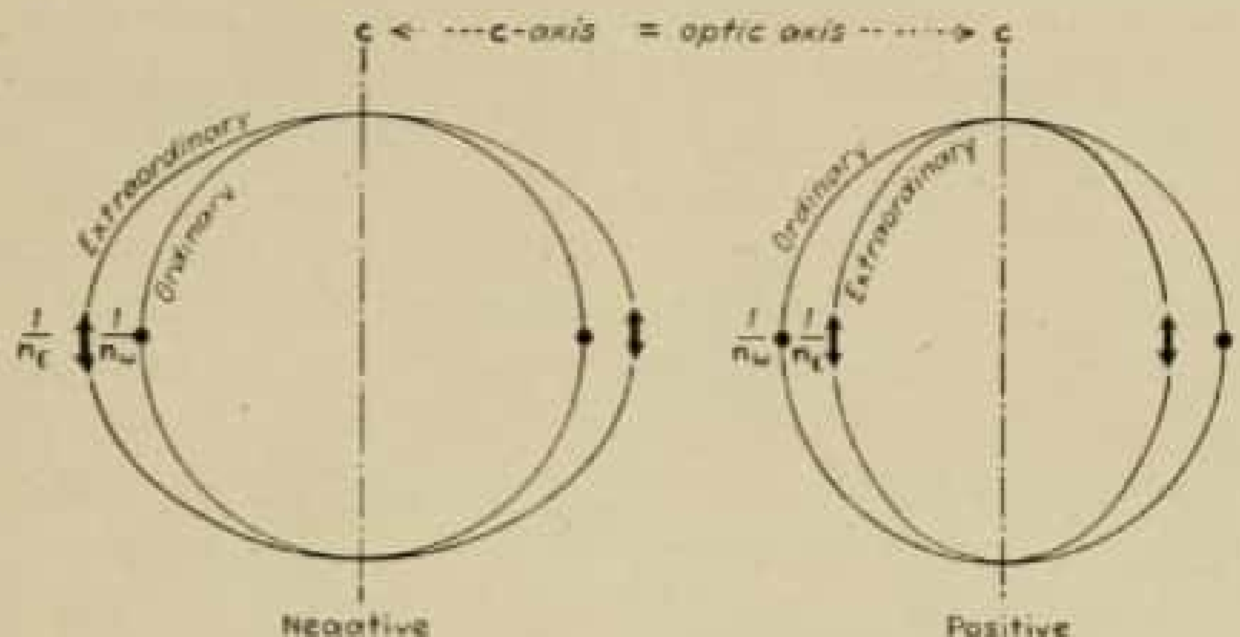


Fig. 76.—Sections of ray surfaces for uniaxial minerals.

a circle. One section of the wave front due to the extraordinary ray would be a circle; the others would be ellipses. Figure 76 illustrates significant sections.

When the velocity of the extraordinary ray is greater than that of the ordinary ray, the ellipse lies outside the circle, and the mineral is optically negative. When the velocity of the ordinary ray is greater than the velocity of the extraordinary ray, the ellipse lies within the circle, and the mineral is optically positive.

$>\omega$ +
= slow
$\omega > \epsilon$ −
= fast

The velocities represented in the diagram Fig. 76 are the reciprocals of the indices of refraction. The ray velocities have equal values in the direction of the *c*-axis, where the circle and ellipse coincide, and have their maximum difference in a direction at right angles to the *c*-axis. The greatest and least indices of refraction occur at right angles to the *c*-axis, and in

$\frac{1}{n}$

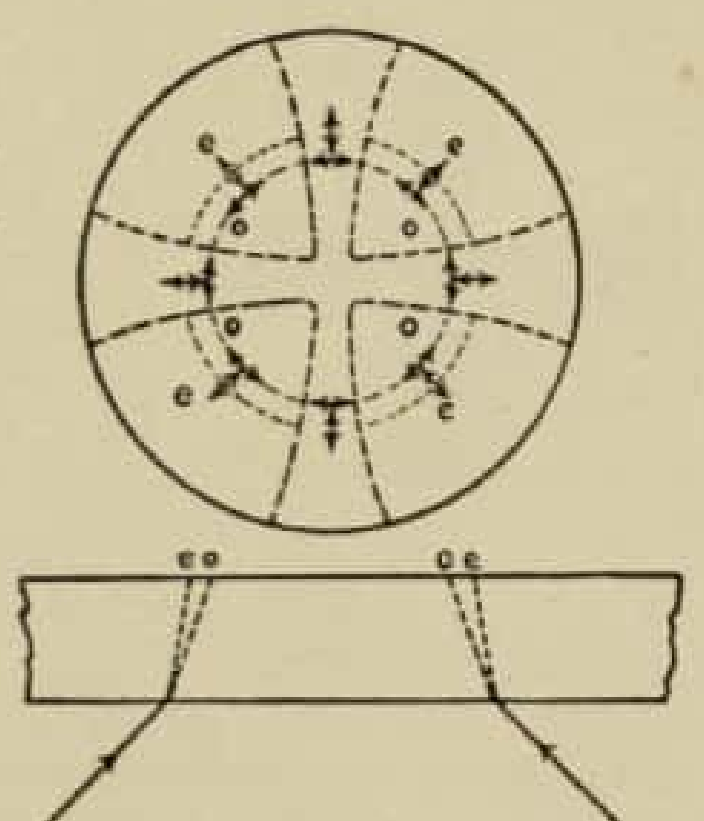


Fig. 77.—Vibration directions in a uniaxial positive interference figure. o = fast ray (least refracted); ϵ = slow ray (most refracted). Velocity of $o = \frac{1}{n\omega}$; velocity of $\epsilon = \frac{1}{n\epsilon}$.

these directions (only) the indices of refraction are the reciprocals of the ray velocities.

The indices of refraction of the two rays at right angles to the c-axis are represented by n_ϵ and n_ω. n_ϵ is the index of the extraordinary ray, n_ω the index of the ordinary ray. In positive minerals n_ϵ is greater; in negative minerals n_ϵ is less.

In Fig. 77 convergent light is shown striking the surface of a mineral plate such as quartz, cut normal to the c-axis. The convergent beam is refracted and broken into two rays. One of the rays, the extraordinary ray e, is more refracted and has the lesser velocity. The other ray, the ordinary ray o, is less refracted and has the greater velocity. Although the diagram is simplified by using two lines to represent the e and o rays, actually there are many multiples of each of the two rays. The radial arrangement, however, obtains throughout.

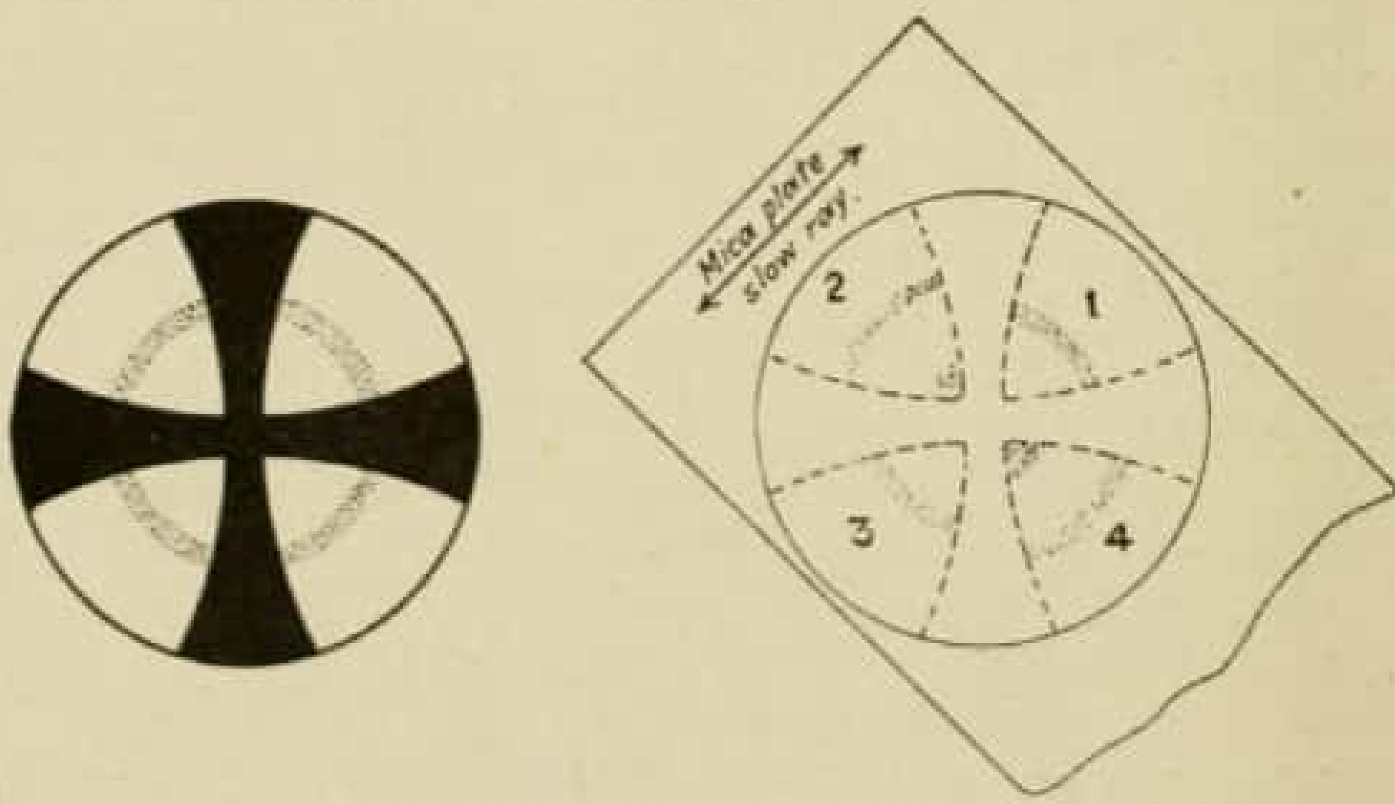


FIG. 78.—Determination of the optic character or sign for a uniaxial positive mineral.

Positive and Negative Sign of Uniaxial Crystals.—As already stated, doubly refracted rays of the uniaxial interference figure are arranged radially as shown in Fig. 77. The extraordinary ray vibrates in the *principal plane* parallel to the c-axis; the other vibrates at right angles. In some minerals the ray vibrating in the principal plane is the slow ray of the crystal; in others it is fast. If it is the slow ray, the mineral is positive; if fast, it is negative. The mineral in the case of Fig. 77 would be optically positive since the slow ray e vibrates parallel to the c-axis.

The position of the slow ray with reference to the *c*-axis may be determined with an accessory plate. If a mica plate, gypsum plate, or quartz wedge is inserted with the slow ray in coincidence with the slow ray of the interference figure, the color bands will change position sufficiently to indicate the optical character of the figure. If the retardation is increased parallel to the slow ray of the interference figure, the mineral is positive. If decreased, the mineral is negative. The movement of the color bands, showing the increase and decrease in retardation when a mica plate is inserted, is illustrated in Fig. 78. The color bands in quadrants 1 and 3 move toward the center; the corresponding color bands in quadrants 2 and 4 move away from the center. The movement in quadrants 1 and 3 represents increase in retardation, whereas that in quadrants 2 and 4 represents decrease in retardation. In the illustration retardation increases parallel to the slow ray since the vibration direction of the slow ray of the mica plate is parallel to quadrants 1 and 3.

Examination of Fig. 79 will show that in the four parts of the circle at 45° to the planes of the nicols the extraordinary and ordinary rays lie in 45° planes or normal to 45° planes. The arrangement is also alternate and opposite.

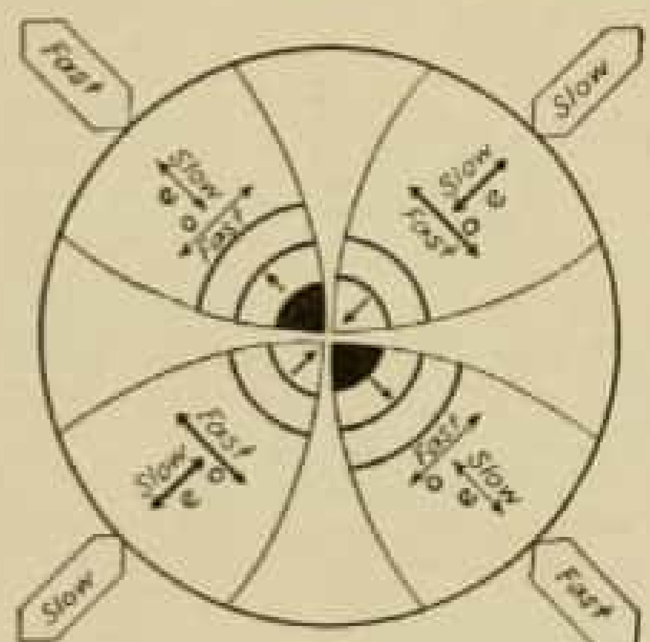


Fig. 79.—The vibration directions in both accessory plate and mineral for a uniaxial positive figure.

The direction of vibration of the slow ray should be marked on each accessory. If a mica plate is inserted with the slow ray in the (1–3) position, the retardation along the extraordinary ray in the (1–3) quadrants will in effect be reinforced. At the same time, an effect of subtraction will occur in the (2–4) quadrants. The color bands of the interference figure will be displaced by this superposition. Where reinforcement occurs, the bands will move toward the center of the circle. Where subtraction occurs, the bands will move in the opposite direction.

In optically positive minerals subtraction occurs at right angles to the direction of the slow ray in the accessory. In negative

minerals the subtraction is in the quadrants lying along the slow-ray direction.

The significant directions are shown in Fig. 79. The diagram indicates the direction of vibration for each of the four quadrants of a uniaxial positive interference figure in the 45° position. Corresponding slow- and fast-ray vibration directions for an accessory plate are indicated along the margins of the interference figure. The ordinary ray *o* is less refracted in the mineral and travels with greatest velocity. The extraordinary ray *e* is more refracted and travels with the least velocity.

In uniaxial negative minerals the situation is reversed. The extraordinary ray will be the fast ray, and the ordinary ray

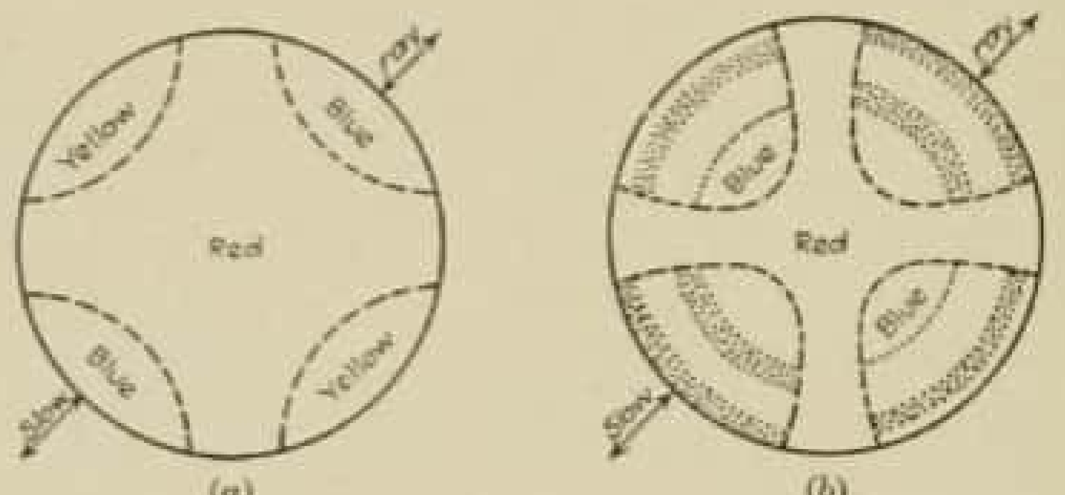


FIG. 80.—(*a*). Uniaxial positive. Quartz cut perpendicular to the optic axis as viewed in the interference figure with a gypsum plate. (*b*) Uniaxial negative. Calcite cut perpendicular to the optic axis as viewed in an interference figure with a gypsum plate.

will be the slow one. The radial arrangement of vibration directions, however, will remain the same. As a result, increase in retardation will occur parallel to the slow ray. When a mica plate is inserted, decrease in retardation produces two black dots in alternate quadrants at the center of an interference figure. The direction of the two dots forms a plus with the vibration direction of the slow ray of the mica plate in positive uniaxial minerals and a minus when the minerals are negative. This relationship serves to keep in mind the fast- and slow-ray vibration directions in uniaxial crystals.

The gypsum plate is frequently more useful for determining the optical character of a uniaxial mineral than is the mica plate. Two bright blue areas form in opposite quadrants of the interference figures of many uniaxial minerals. These stand out particularly in figures given by minerals of moderate or inter-

mediate double refraction. When the optical character is positive, as in the case of quartz, the two blue areas occur in opposite quadrants parallel to the slow-ray vibration direction of the gypsum plate (see Fig. 80*a*). When the optical character is negative, as in the case of calcite, the two blue areas occur in opposite quadrants at right angles to the slow-ray vibration direction of the gypsum plate (see Fig. 80*b*).

Biaxial Interference Figures. *Introduction.*—Under normal conditions minerals crystallizing in the orthorhombic, monoclinic, and triclinic crystal systems give biaxial interference figures. Rarely, because of crystallization under strain, hexagonal or tetragonal minerals, normally uniaxial, are anomalous and produce biaxial figures. The latter, however, are exceptions to the general rule.

Double refraction, orientation, and thickness of section govern the character of biaxial interference figures as rigidly as in the case of uniaxial interference figures. Biaxial interference figures are also produced by the same optical arrangement of the microscope employed in the case of uniaxial figures. Unlike uniaxial figures, curves of biaxial figures assume different relative forms as the stage is rotated.

Figure 73 illustrates the two different forms of a biaxial interference figure given by a mineral at 90° and 45° intervals of rotation of the microscope stage. The 45° position is the most useful for ordinary optical determinations and is ordinarily employed in the study of biaxial minerals. The figure in this position is described as an *acute bisectrix* figure at 45°.

The 45° Acute Bisectrix Figure.—Figure 81 indicates the nomenclature of the parts of an acute bisectrix figure at 45°. The different features may be described as follows:

Isogyres.—The two broad black curves, or brushes, which mark the areas of extinction, are known as isogyres. Strong dispersion produces red and blue fringes on the margins of the isogyres. By noting the distribution of the colored fringes in the interference figure one determines the character of the dispersion. In minerals with strong dispersion the curves are not so black or so sharp as in the case of minerals with weak dispersion.

Points of Emergence of the Optic Axes.—The vertices of the two crescentlike curves mark the points of emergence of the optic axes. The amount of separation of these points differs with

different minerals but is a constant for an individual mineral The line between the two points of emergence subtends the optic axial angle.

Johannsen has suggested the word *melatope* for the points of emergence.

Plane of the Optic Axes.—The plane of the optic axes, or axial plane, includes the two points of emergence of the optic axes, the acute bisectrix direction, and the obtuse bisectrix direction.

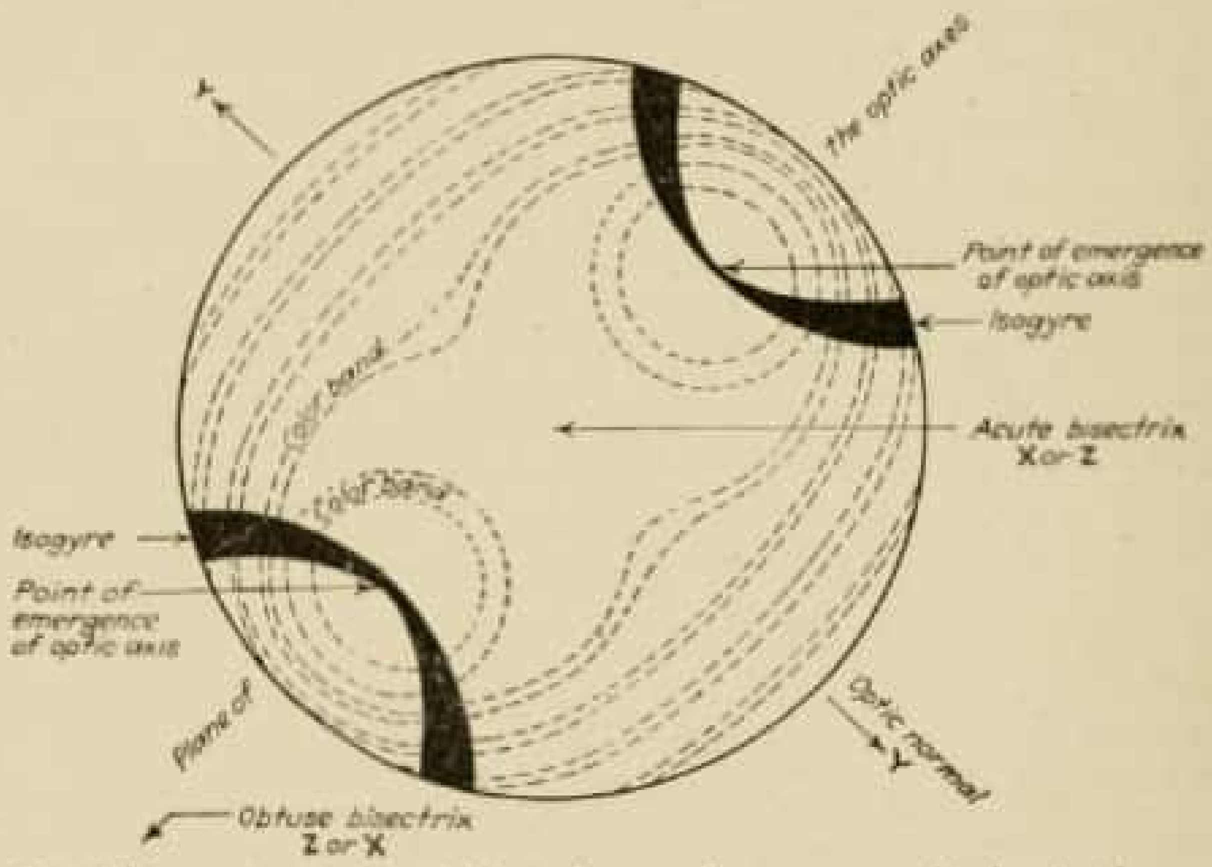


FIG. 81.—The parts of a biaxial interference figure perpendicular to the acute bisectrix in the 45° position.

Color Bands.—Interference color bands representing positions of equal retardation are distributed in symmetrical curves around the points of emergence of the optic axes and are called *isochromatic curves.*

X, Y, and Z: The three axes X, Y, and Z are distributed in the interference figure as shown in the diagram. Y is normal to the plane of the optic axes. If the acute bisectrix is X, the obtuse bisectrix is Z, and vice versa.

Optic Normal.—The direction at right angles to the plane of the optic axes is referred to as the optic normal. It is the axis Y.

Eccentric Biaxial Figures.—Since biaxial minerals as observed in thin section may be cut at any angle, a variety of modifications of the biaxial interference figures result. A single isogyre may swing across the field in one figure, another may yield an optic

axis, another may show the acute bisectrix, etc. The most useful figures for optical determinations of mineral properties are either acute bisectrix or optic-axis figures. In optic-axis figures (see Fig. 93) the convex side of the isogyre in the 45° position indicates the direction of the acute bisectrix.

Optic-axis figures and most acute bisectrix figures are given by mineral sections showing comparatively low-order colors between crossed nicols in parallel light. Examination of a number of crystals of miscellaneous orientation between crossed nicols will often quickly reveal those most likely to give interference figures of useful orientation in convergent light.

Optical Directions in Biaxial Minerals.—In all biaxial minerals the various optical features may be conveniently oriented by reference to three axes, X, Y, and Z, arranged at right angles to each other. X, Y, and Z indicate the ease of vibration of light in the mineral. Light traveling normal to X vibrates parallel to the axis and has the maximum velocity for the mineral $1/n_\alpha$. Light traveling normal to Z vibrates parallel to the axis and has the minimum velocity for the mineral $1/n_\gamma$. The axis Y lies at right angles to the plane of X and Z. Light traveling normal to Y vibrates parallel to the axis and has an intermediate velocity $1/n_\beta$.

In a given mineral, light vibrating parallel to X will form the fast ray. Light vibrating parallel to Z is the slow ray, and light vibrating parallel to Y will be intermediate in velocity. Thus, when the direction of observation lies along the X-axis, XZ will indicate the slow ray and XY the intermediate ray; similarly, when the direction of observation is the Z-axis, ZX will be the fast ray and ZY the intermediate ray. When the direction of observation is the Y-axis, YX will be the fast ray and YZ the slow ray.

The fast- and slow-ray directions corresponding to the various directions of observation along the axes may be indicated as shown in the table on page 98.

When the direction of observation lies along the X-axis, light vibrating parallel to the plane XZ will have the greatest index of refraction, and light vibrating parallel to the plane XY will have an intermediate index of refraction. When the direction of observation lies along the Z-axis, light vibrating parallel to the plane ZX will have the least index of refraction, and light vibrat-

Direction of observation	Two rays observed	Velocities
X	Faster ray Slower ray	$1/n_\beta$ = intermediate ray $1/n_\gamma$ = slowest ray
Y	Faster ray Slower ray	$1/n_\alpha$ = fastest ray $1/n_\gamma$ = slowest ray
Z	Faster ray Slower ray	$1/n_\alpha$ = fastest ray $1/n_\beta$ = intermediate ray

ing parallel to ZY will have an intermediate index of refraction. When the direction of observation lies along the Y-axis, light vibrating parallel to the plane YX will have the least index of refraction, and parallel to YZ will have the greatest index of refraction.

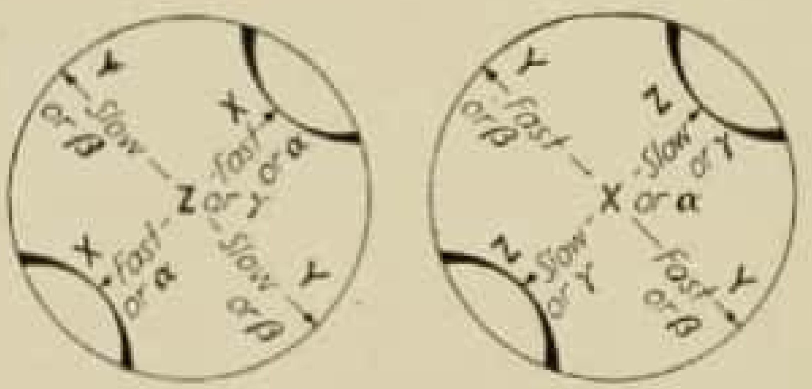


FIG. 82.—Ease-of-vibration directions X, Y, and Z, or α, β, and γ, with reference to biaxial positive and negative interference figures. Corresponding fast and slow ray directions are also indicated.

Within certain limits, the axes X, Y, and Z have positions in minerals that are dependent upon the system of crystallization. In orthorhombic minerals, X, Y, and Z are fixed with respect to the crystallographic axes *a*, *b*, and *c*. In the monoclinic system one of the three axes (often Y) coincides with the crystallographic axis *b*. In the triclinic system there are no limitations of position according to the crystallographic axes.

The optical directions in biaxial minerals may be represented in several ways. One of the most generally used devices is the ray surface illustrated in Fig. 83. Another is the index ellipsoid of Fig. 85. The ray surface is developed on X, Y, and Z arranged at right angles to each other. The index ellipsoid (optical indica-

trix) may be developed on the same axes, but by convention α, β, and γ are usually used instead of X, Y, and Z. The accompanying table furnishes a comparison of the two systems of representation.

COMPARISON OF THE BIAXIAL RAY SURFACE AND THE INDEX ELLIPSOID

Comparative features	Distance from center to surface	
	Biaxial ray surface	Index ellipsoid
Axial directions		
Least velocity	Z	γ
Greatest velocity	X	α
At right angles	Y	β
Major semi-axis	$1/n_\alpha$ and $1/n_\beta$	n_γ
Intermediate semi-axis	$1/n_\alpha$ and $1/n_\gamma$	n_β
Minor semi-axis	$1/n_\gamma$ and $1/n_\beta$	n_α
Optic axes	Secondary optic axes or biradials	Primary optic axes or binormals
Surface	Double	Single

The correlation of the ease-of-vibration directions, whether designated by X, Y, and Z or α, β, and γ, with biaxial interference figures of different sign is shown in Fig. 82.

Let us assume a single crystalline mass of a biaxial crystal of sufficient size to allow examination of light variation in the system. If light were to radiate out from the center of a solid mass of such an anisotropic medium, at a given instant the wave front produced would be a double-sheeted surface with sections as illustrated in Fig. 83. The optic axes lie in the plane of X and Z and the acute angle $2V$ between the optic axes varies between 0 and 90°.

If the axis Z is the bisectrix of the acute angle between the optic axes, the mineral is said to be optically positive. If the axis X is the acute bisectrix, the mineral is said to be optically negative.

Two wave fronts appear in each section along the axes—one a circle, the other an ellipse. The size of each circle is determined by the velocity of the light ray vibrating parallel to the axis around which it is generated. Around X the radius of the circle is $1/n_\alpha$; around Y the radius is $1/n_\beta$; and around Z it is $1/n_\gamma$. Since n_α is the least index of refraction and $1/n_\alpha$ indicates the

greatest velocity for the system, the circle around X is the greatest. Since $1/n_\beta$ is intermediate in velocity, the circle around Y will have intermediate size. Since $1/n_\gamma$ represents the least velocity, the circle around Z will be smaller than the circles around the two other axes. Three combinations of ellipses and circles are represented. In the section perpendicular to Y and in the plane XZ, the circle with radius $1/n_\beta$ intersects an ellipse with major and minor semi-axes $1/n_\alpha$ and $1/n_\gamma$, respectively. In the section perpendicular to Z and in the plane XY, the smallest circle, radius $1/n_\gamma$, lies within the ellipse with major and minor

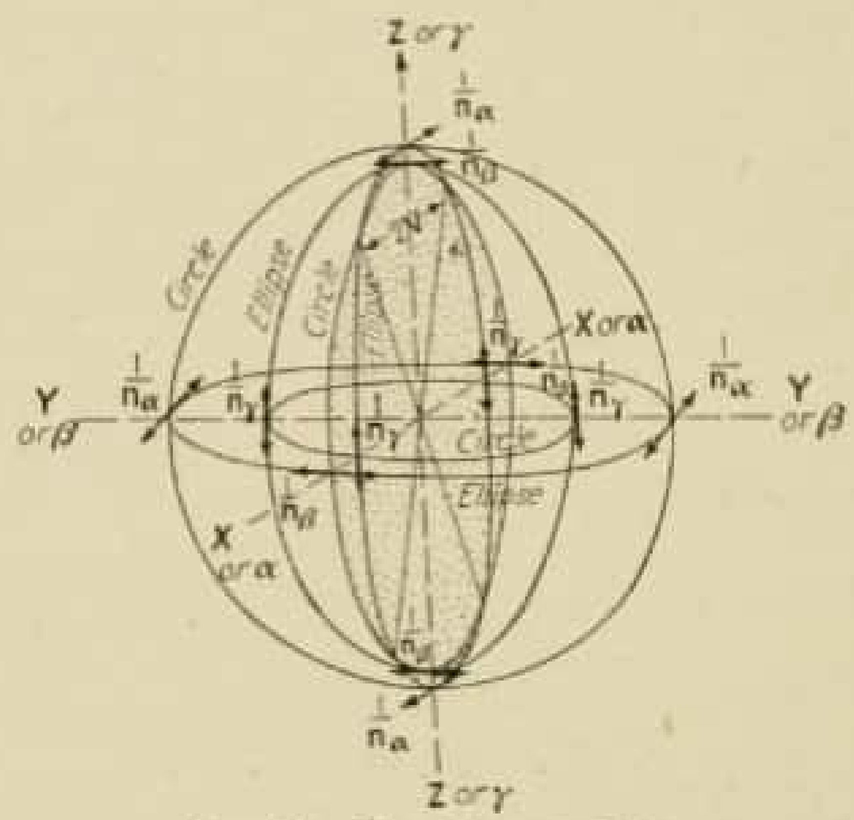


FIG. 83.—Biaxial ray surface.

semi-axes $1/n_\alpha$ and $1/n_\beta$, respectively. In the section perpendicular to X in the plane YZ the largest circle, radius $1/n_\alpha$, lies outside the ellipse with major and minor semi-axes $1/n_\beta$ and $1/n_\gamma$, respectively.

Light vibrating parallel to Z will radiate outward from the center in the plane XY. The wave front will be circular, and the velocity will be $1/n_\gamma$. Similarly, light vibrating parallel to X will travel outward in the plane YZ with a circular wave front, and the velocity will be $1/n_\alpha$. Likewise, light vibrating parallel to Y will travel in the plane XZ with a circular wave front and a velocity $1/n_\beta$. In each of these instances n_α, n_β, and n_γ represent, respectively, the least, intermediate, and greatest indices of refraction of the mineral.

The planes XY, YZ, and XZ are especially significant. Sections along each of these planes are illustrated in Fig. 84, *a*, *b*, and *c*.

In the plane XZ the ellipse and circle will cross at four points. At these four points no difference in wave velocity exists. These points of intersection mark the positions of the *secondary optic axes*, or *biradials*. In most crystals these secondary optic axes lie very near the *primary optic axes* but are not identical with them.

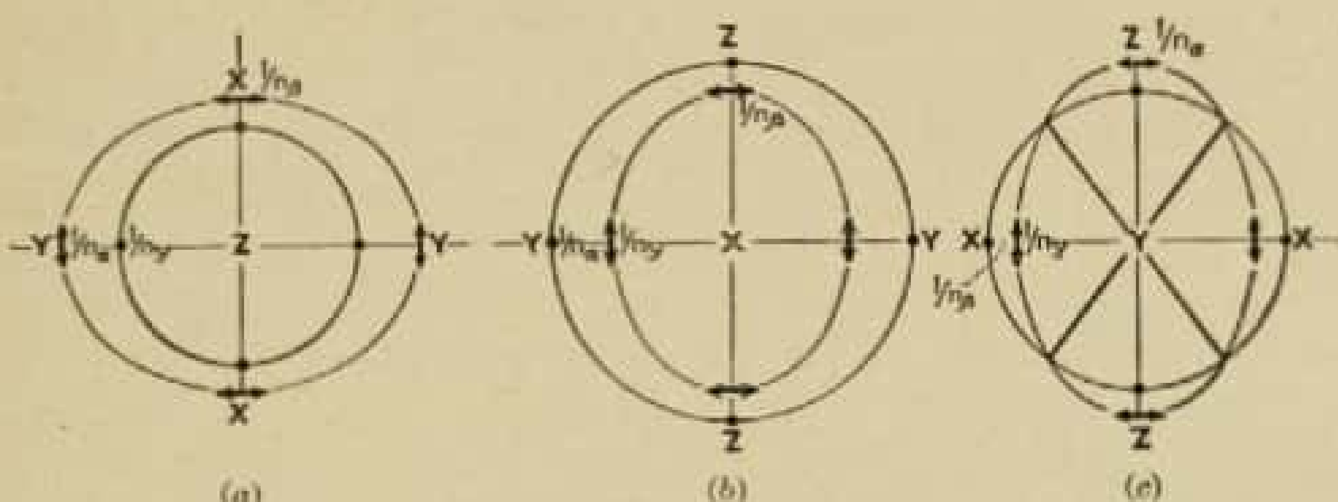


Fig. 84.—Sections of biaxial ray surface. (*a*) Section perpendicular to Z. (*b*) Section perpendicular to X. (*c*) Section perpendicular to Y.

Index Ellipsoid (Optical Indicatrix).—It is often found more convenient to represent the optical relations of crystals by means of a figure called the *index ellipsoid* (Fig. 85) than by the biaxial ray surface (Fig. 83). The index ellipsoid is also a three-dimensional figure but differs materially in development from the biaxial ray surface. The biaxial ray surface consists of two intersecting surfaces, whereas the exterior of the index ellipsoid is a single surface. The major, minor, and intermediate axes upon which the two are based also differ materially. The biaxial ray surface is based upon axes that are proportional to the reciprocals of the refractive indices. The index ellipsoid, on the other hand, is based upon axes directly proportional to the refractive indices.

The index ellipsoid or optical indicatrix for biaxial crystals may be described as a triaxial ellipsoid. In common with all triaxial ellipsoids the surface is symmetric in the origin, and in the coordinate axes and coordinate planes. The origin is the *center* of the ellipsoid, the coordinate axes are the *axes* of the ellipsoid, and coordinate planes are the *principal planes* of the ellipsoid.

The diameters of the index ellipsoid measured along the axes are $2n_\alpha$, $2n_\beta$, $2n_\gamma$. These values correspond in order to the

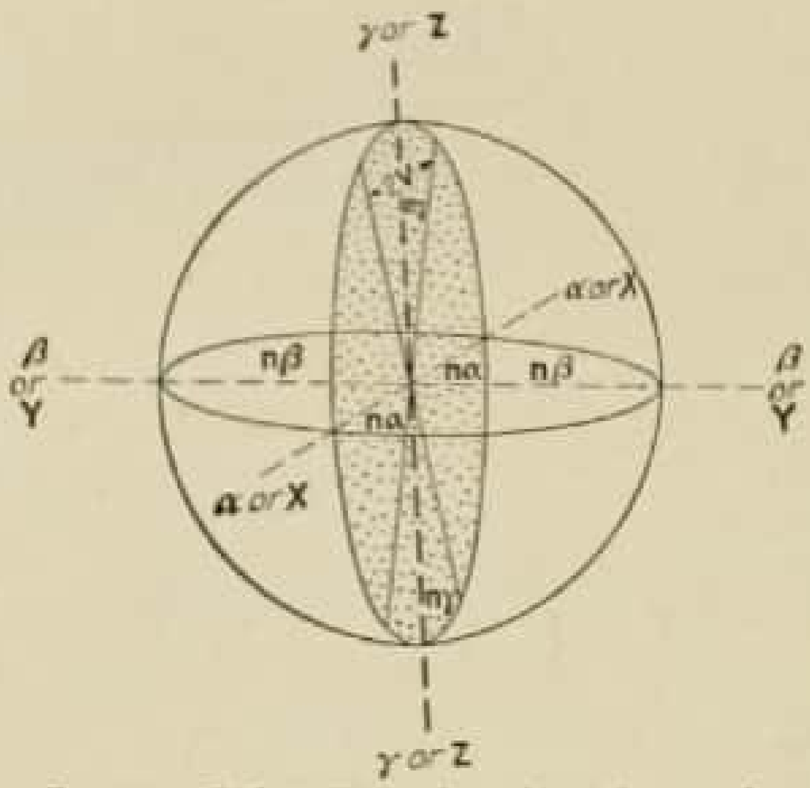


Fig. 85.—Index ellipsoid for biaxial crystals.

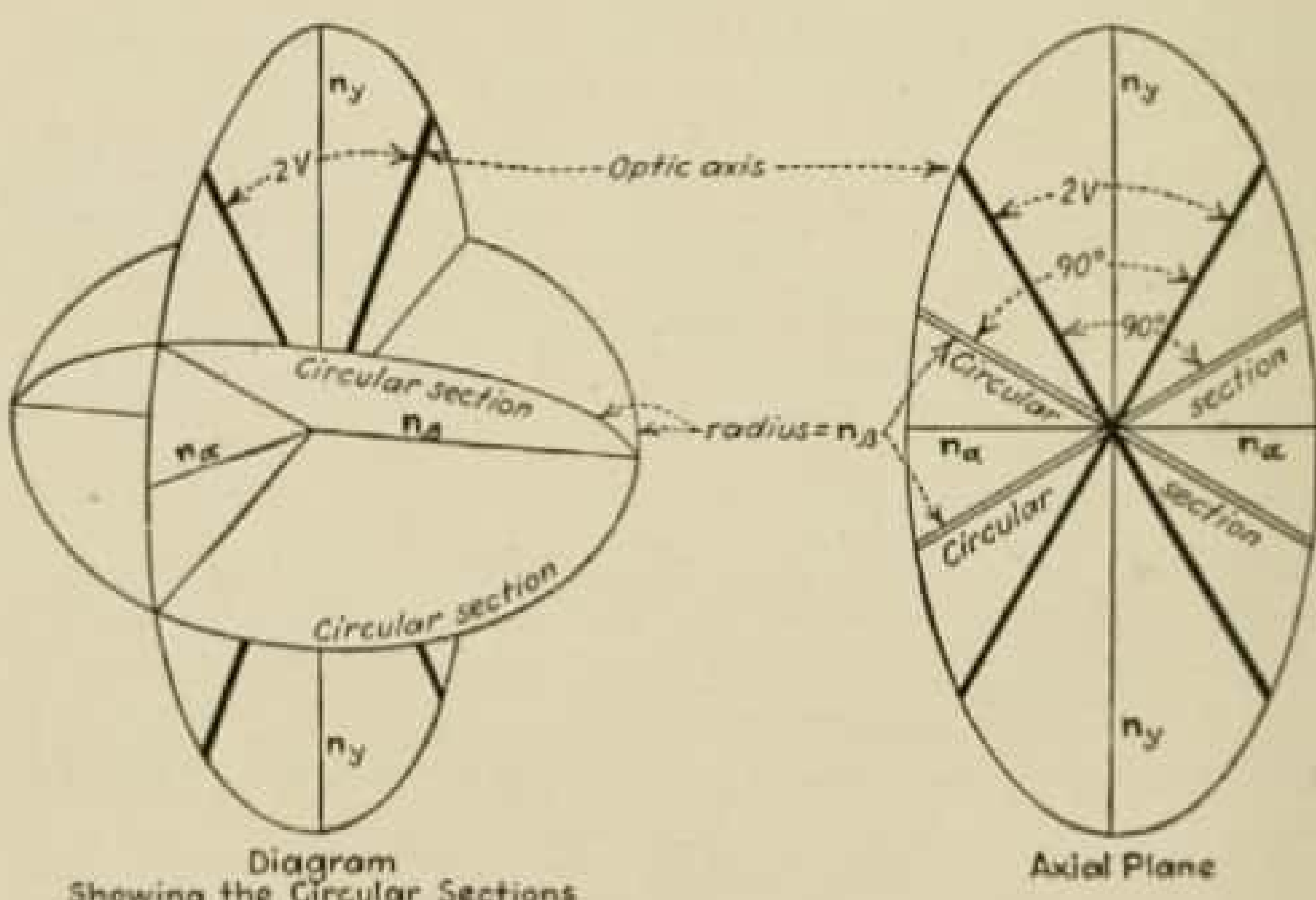


Fig. 86.—The relationship between the two circular sections, the optic axes, and ellipsoidal axes (n_α, n_β, and n_γ) in the index ellipsoid.

minor, intermediate, and major axes of the ellipsoid. The sections cut by the principal planes are the *principal sections* of

the ellipsoid. These sections are ellipses and have as major and minor diameters combinations of $2n_\alpha$, $2n_\beta$, and $2n_\gamma$.

All except two of the plane sections of the index ellipsoid that are cut through the center are ellipses. These are circles (Fig. 86). The two circular sections include the semi-axis with length n_β, and thus the length of the radius of each circular section equals n_β. The directions perpendicular to the two circular sections are called the *optic axes*, or *binormals*. These are sometimes called the *primary optic axes* and differ slightly from the secondary optic axes (biradials) of the biaxial wave surface.

The index ellipsoid for uniaxial crystals provides a special case. In such crystals two of the diameters have the same value, $2n_\omega$. As a result, the principal section containing the two diameters, each having the value $2n_\omega$, is a circle. The surface of this indicatrix is an ellipsoid of revolution.

The index ellipsoid for isometric crystals is another special case. The three diameters have equal values, $2n$, and the surface developed is a sphere.

The optical properties of light rays may be determined in any given direction in a triaxial ellipsoid. Let us suppose Fig. 87 to represent the ellipsoid. The semi-axes are n_γ, n_β, and n_α, respectively, and $S'S$ represents the direction of propagation of light along a given line. If the direction of $S'S$ has been determined or is known, the following three pairs of optical properties become known by construction:

1. The vibration directions of the two rays traveling along $S'S$.
2. The two corresponding indices of refraction, n_2 and n_1.
3. The directions of the two wave normals.

If the direction of the diameter $S'S$ is known, the position of the planes tangent to $S'S$ at the two ends of the diameter also becomes known. It is then possible to pass a parallel diametral plane through the ellipsoid intersecting the center and equidistant between the two tangent planes. The diametral plane through the center will cut an elliptical section in all but two possible positions of $S'S$. These two exceptional positions are the optic axes, and here the sections cut are circular (Fig. 87). The elliptical section furnishes measurements from which the optical properties can be determined. The diametral plane will have major and minor axes. These axes mark the vibration directions of the two rays traveling along $S'S$. The major and

minor radii represent the refractive indices of the waves associated with the two rays, equaling n_2 and n_1. The wave normal corresponding to the ray propagated along $S'S$ and vibrating along the major axis lies in a plane through $S'S$ and the major axis and is normal to the axis. Similarly, the wave normal corresponding to the ray propagated along $S'S$ and vibrating along the minor axis lies in a plane through $S'S$ and the minor axis and is normal to the axis.

Drop perpendiculars from the intersection of the axes with the circumference of the ellipse (Figs. 87 and 88) upon $S'OS$; these

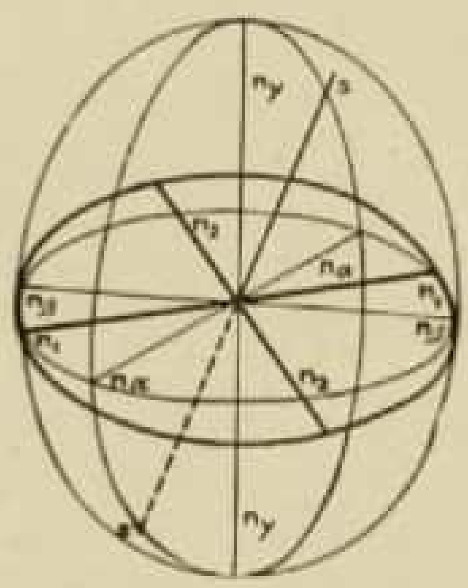


FIG. 87.—A ray OS in an index ellipsoid with a conjugate plane through O and parallel to tangent planes at S and S'.

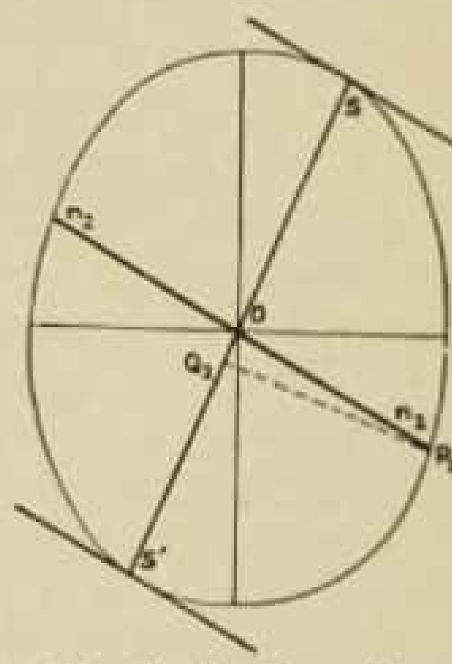


FIG. 88.—Section through an ellipsoid showing the ray OS together with traces of tangent and diametral planes.

perpendiculars are P_2Q_2 and P_1Q_1. Then $1/P_2Q_2$ is the velocity of the ray propagated along $S'OS$ and vibrating along the major axis, and $1/P_1Q_1$ is the velocity of the ray propagated along $S'OS$ and vibrating along the minor axis. P_1Q_1 lies in a plane at right angles to the plane of the drawing in Fig. 88.[1]

The Axial Angles 2E and 2V.—The observed axial angle is always greater than the true axial angle within the mineral. This is due to the refraction of the oblique rays, as illustrated in Fig. 89. The angle $2E$ is the angle in air, while $2V$ is the internal angle.

[1] The foregoing discussion is largely based upon a paper, The Ray Surface, the Optical Indicatrix, and Their Interrelation, by Dr. George Tunell (*Wash. Acad. Sci.*, 1933).

Mallard's equation ($D = K \sin E$) may be used to determine the approximate axial angle with the microscope. In the equation K is a constant for a particular microscope, D is one-half the distance between the points of emergence, and E is one-half the axial angle in air. When $2E$ has been determined the next step is to compute $2V$.

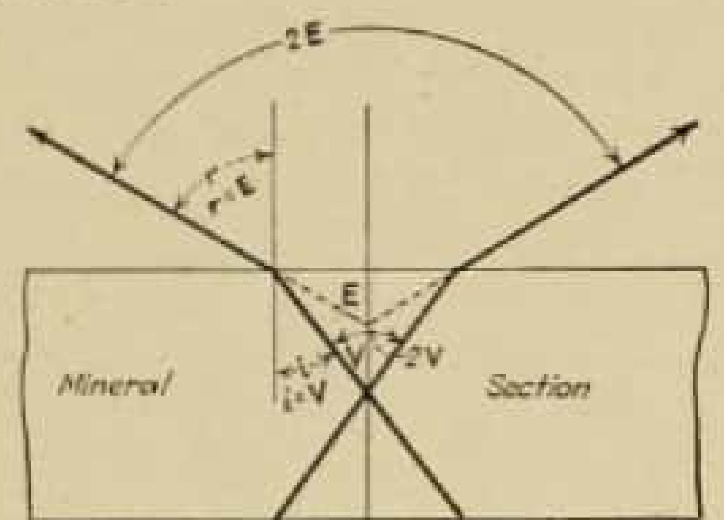
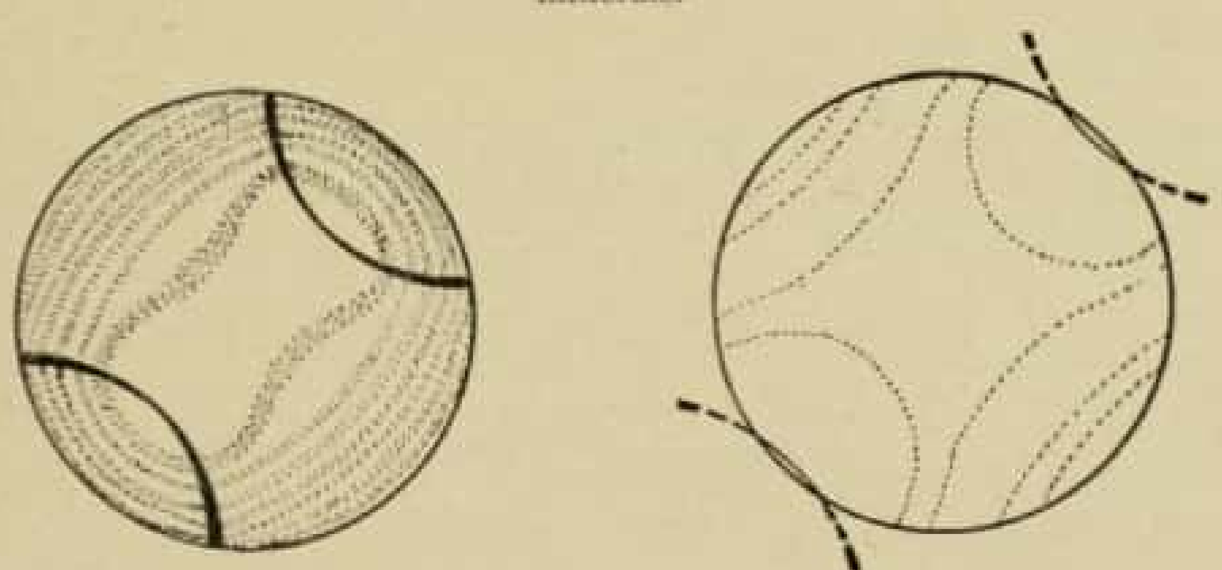


FIG. 89.—The relation between the observed angle $2E$ and the angle $2V$ in biaxial minerals.



(a) Aragonite
$2V = 19°$
$n_\gamma - n_\alpha = 0.155$

(b) Barite
$2V = 37°30'$
$n_\gamma - n_\alpha = 0.012$

FIG. 90.—Comparison of axial angles.

The computation of the axial angle in a mineral from the observed axial angle in air depends upon the formula

$$\sin E = n_\beta \sin V$$

When $n \sin V$ is equal to 1, the angle $2E$ becomes 180°, and the axial angle in air cannot be measured. Angles greater than 180° likewise cannot be measured in air. The value of the observed angle may be reduced to measurable dimensions by immersing the objective in oil of known refractive index.

Large axial angles need to be measured with a rotation device. Such devices for rotating crystals in a vertical circle may be adapted to the stage of the microscope; otherwise special apparatus must be employed.

Variation in Axial Angle.—Figure 90 illustrates two biaxial interference figures in the 45° position. The figures represent two different minerals—aragonite on the left and barite on the right. The two sections from which the interference figures are derived have been cut normal to the acute bisectrix in each instance, and the sections are also of approximately the same thickness. As a result of these conditions, only two variables remain to produce differences in the diagram: variation in the axial angle $2V$ and variation in the double refraction $n_2 - n_1$.

The isogyres in the figure on the left represent the approximate position of the two curves in relation to the field of the microscope for an axial angle $2V = 19°$ (aragonite). The figure on the right represents barite drawn to the same scale. In this instance the angle $2V = 37°30'$ places the isogyres at the edge of the field of view.

The dotted lines in the figures indicate the distribution of the color bands. Aragonite has a double refraction of 0.155, which is considerably larger than the double refraction of barite, which is 0.012. In consequence, for the same thickness of section, aragonite has many more color bands than barite.

The student should study the interference figures of a number of different mineral sections cut normal to the acute bisectrix until he becomes familiar with the variation of the isogyres with the axial angle. In fact, it is worth while to record in a notebook the relative positions of the isogyres for angles in the neighborhood of 5, 10, 15, 20, 25, 30, 35, and 40°. A record of this sort will be of considerable assistance in determining the approximate axial angle of an unknown mineral.

It should also be remembered that if the thickness remains the same, the number of the color bands of the interference figures will either increase or decrease with increase or decrease in the double refraction.

Determination of the Optic Sign of a Biaxial Mineral.—The optic sign is best determined with the mineral in the 45° position. The quartz wedge is employed for most determinations. In some cases, however, a mica plate or gypsum plate may be pre-

ferred. The same principles utilized when the quartz wedge is employed apply equally in determinations with the other accessory plates.

As stated before, X, Y, and Z are the axes of ease of vibration. Light traveling through a crystal normal to X has the maximum velocity for all directions in the crystal. Light traveling normal to Z has the least velocity. The direction Y is normal to the plane of X and Z. When the direction X is the acute bisectrix, the mineral is optically negative. If Z is the acute bisectrix, the mineral is positive.

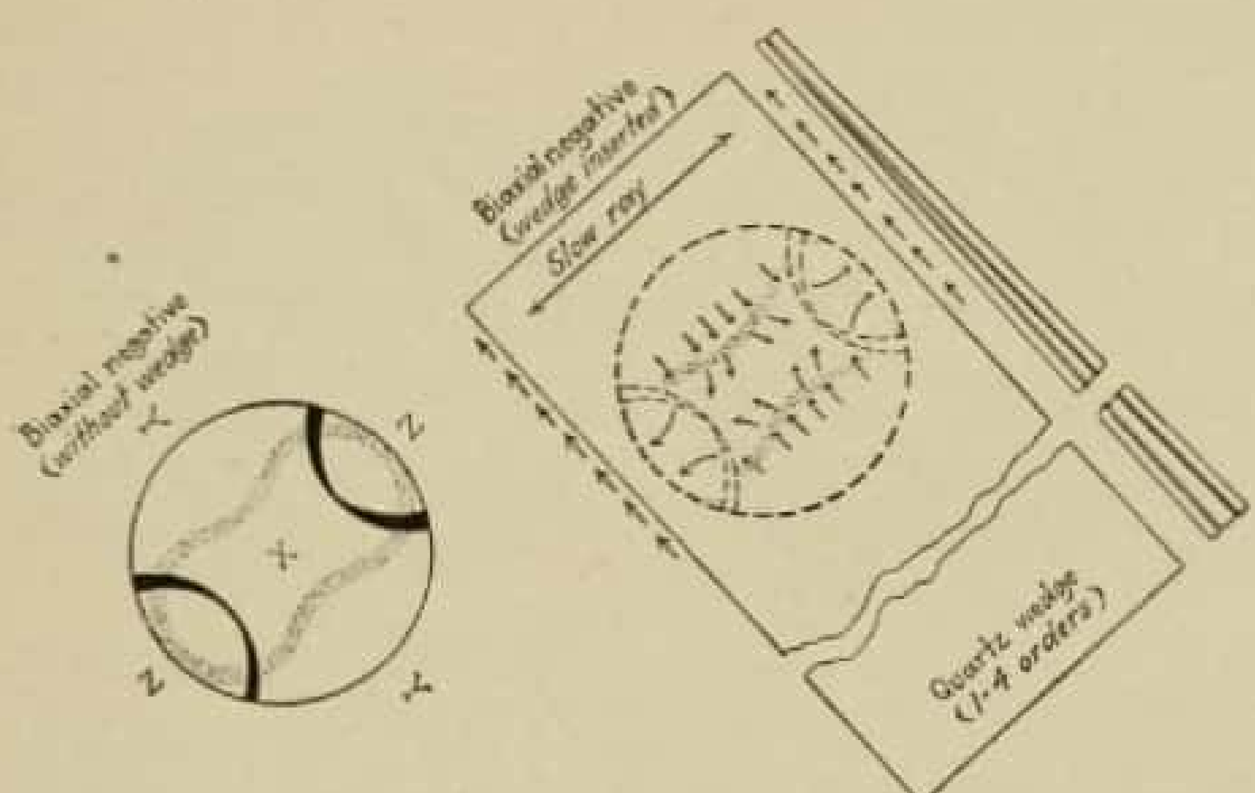


Fig. 91.—The determination of the optic sign with a biaxial negative interference figure.

A biaxial negative crystal in the acute bisectrix position at 45° will be used to illustrate the method of determining the optic sign (see Fig. 91). A biaxial figure of this type is first observed carefully in order to note the position of the color bands, both in the central area and within the two small areas inclosed by the concave portions of the isogyres. A quartz wedge is then inserted in the accessory slot with the slow ray parallel to the axial plane. Movement of the color bands occurs as the wedge is inserted.

The movement of the color bands in a negative crystal is indicated by the arrows in Fig. 91. As the wedge is moved in—*i.e.*, as the thickness increases—the color bands in the central area move toward the two "eyes," or melatopes, of the interference figure. At the same time the bands on the opposite sides

of the isogyres within the two small areas move away from the melatopes. As the wedge is withdrawn, the movement of the color bands is reversed. If a positive crystal is substituted, the movement of the color bands is also reversed.

In the biaxial negative crystal illustrated the axis Z lies in the axial plane along the direction of the obtuse bisectrix. The axis X is perpendicular to Z and is the direction of the acute bisectrix. The axis Y is the optic normal. Two rays travel along X with vibration directions at right angles to each other, the vibration directions being parallel, respectively, to Z and Y. The ray vibrating parallel to Z is the slow ray for the crystal (velocity

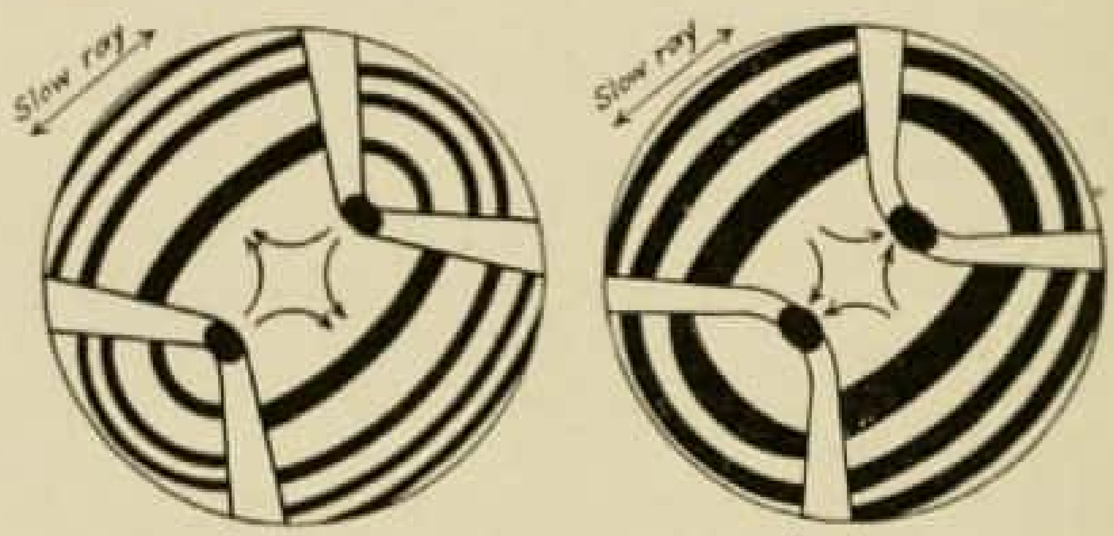


FIG. 92.—Positive and negative biaxial crystals (indicating their appearance with a mica plate in monochromatic light).

$(1/n_\gamma)$; that parallel to Y is intermediate in velocity, having the value $1/n_\beta$. Thus, in the central area of the interference figure at X, we have a slow ray, velocity $1/n_\gamma$, and an intermediate but faster ray, velocity $1/n_\beta$. Consequently, if the slow ray of the quartz wedge is parallel to the direction Z, increase in retardation occurs as the wedge thickness increases. This results in a movement of the color bands toward the melatopes in the central portion of the figure as the wedge is inserted. At the same time the color bands in the outer portions will move in the opposite direction since here the slower ray and faster ray relations are reversed. If the quartz wedge is always inserted as indicated in Fig. 91, an acute bisectrix biaxial negative interference figure in the 45° position will always show movement of the color bands toward the melatopes in the central area. Conversely, a biaxial positive figure treated in the same way will show movement in the opposite direction. Since the slow-ray vibration direction

in the quartz wedge is marked, the slow-ray vibration direction in the interference figure is easily determined by comparison. Examples of both positive and negative biaxial figures in monochromatic light with the slow-ray vibration direction of an accessory plate superimposed are shown in Fig. 92.

The Optic-axis Figure.—Interference figures produced by sections cut normal or nearly normal to one of the two optic axes of a biaxial mineral are useful for determinations of optic sign. Such sections yield interference figures having a single isogyre in the field of view. The melatope, or point of emergence, may coincide with the axis of the microscope or may be slightly off center.

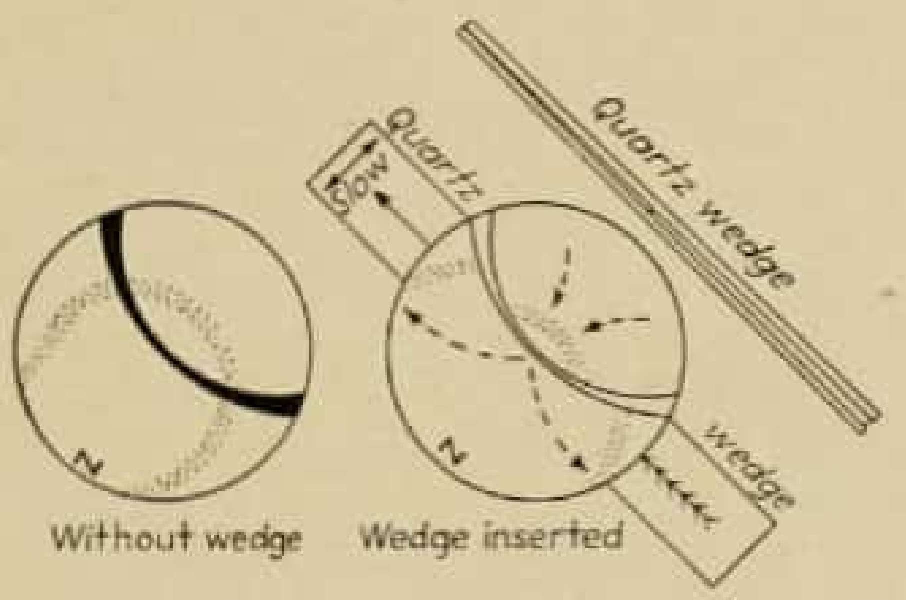


FIG. 93.—Movement of the color bands in an optic-axis biaxial positive interference figure as an accessory plate is inserted.

As the stage is rotated, the isogyre swings around the field, remaining centered or nearly centered, depending upon the eccentricity of the section. The color bands are arranged almost circularly around the melatope and vary in retardation with the double refraction of the mineral.

The curvature of the isogyre decreases with an increase in $2V$. When the axial angle is large—*i.e.*, near 90°—the isogyre is straight, and the acute bisectrix side of the interference figure becomes indistinguishable from the obtuse bisectrix side. When the angle is small, however, the isogyre is definitely curved in a crescentlike form. The convex side of the curve in the 45° position points toward the acute bisectrix, and the obtuse bisectrix is on the concave side.

Optic-axis figures showing even slight curvature are useful for determinations of the optic sign. The mica plate, gypsum

plate, or quartz wedge may be employed, depending upon the double refraction of the mineral. The effect of the quartz wedge upon a biaxial positive optic-axis interference figure is shown in Fig. 93. An optic-axis figure without the wedge inserted is shown on one side of the diagram, and the movement of the color bands caused by insertion of the wedge is shown on the opposite side.

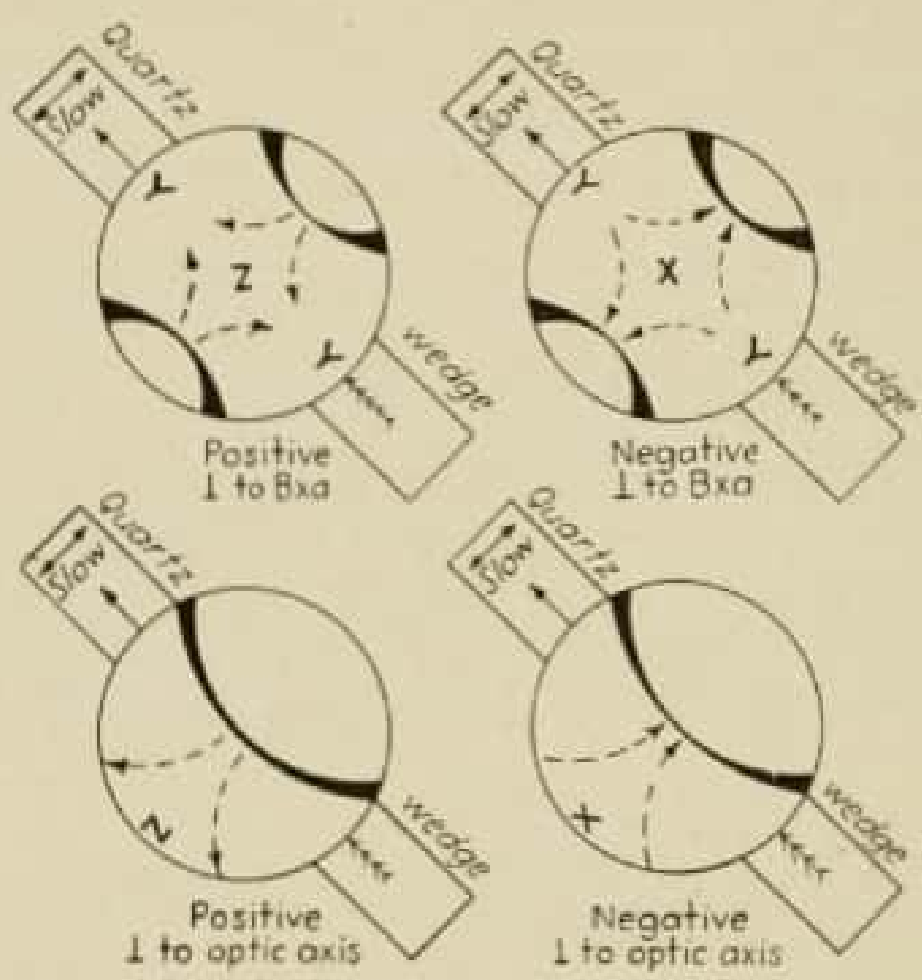


Fig. 94.—Movement of the color bands to be expected as the quartz wedge is inserted in acute bisectrix and optic-axis interference figures of opposite sign.

Diagrams are shown in Fig. 94, which should be of convenience in determining the signs of interference figures in the two most useful positions upon insertion of the quartz wedge. The same principles apply in utilizing mica and gypsum plates.

Dispersion in Biaxial Interference Figures.—The optic angle for light of one wave length is frequently greater or less than for light of another wave length. In the normal interference figure produced by white light this is usually detected by a peculiar arrangement of the color bands or by the development of blue and red fringes on the isogyres.

The dispersion recorded in most tables of optical mineralogy is that of the optic axes. The two extreme rays of the spectrum

are used to designate the character of the dispersion. Thus, if the axial angle for red r is greater than that for violet v, the dispersion is expressed $r > v$. In case the reverse is true, the formula is $r < v$.

In many instances the dispersion can be determined by direct observation of the biaxial interference figure (Fig. 95). If the isogyres of the interference figure ($r > v$) have a distinct red fringe on the convex edges, the angle for red is greater than for violet. Both isogyres should be observed before reaching a

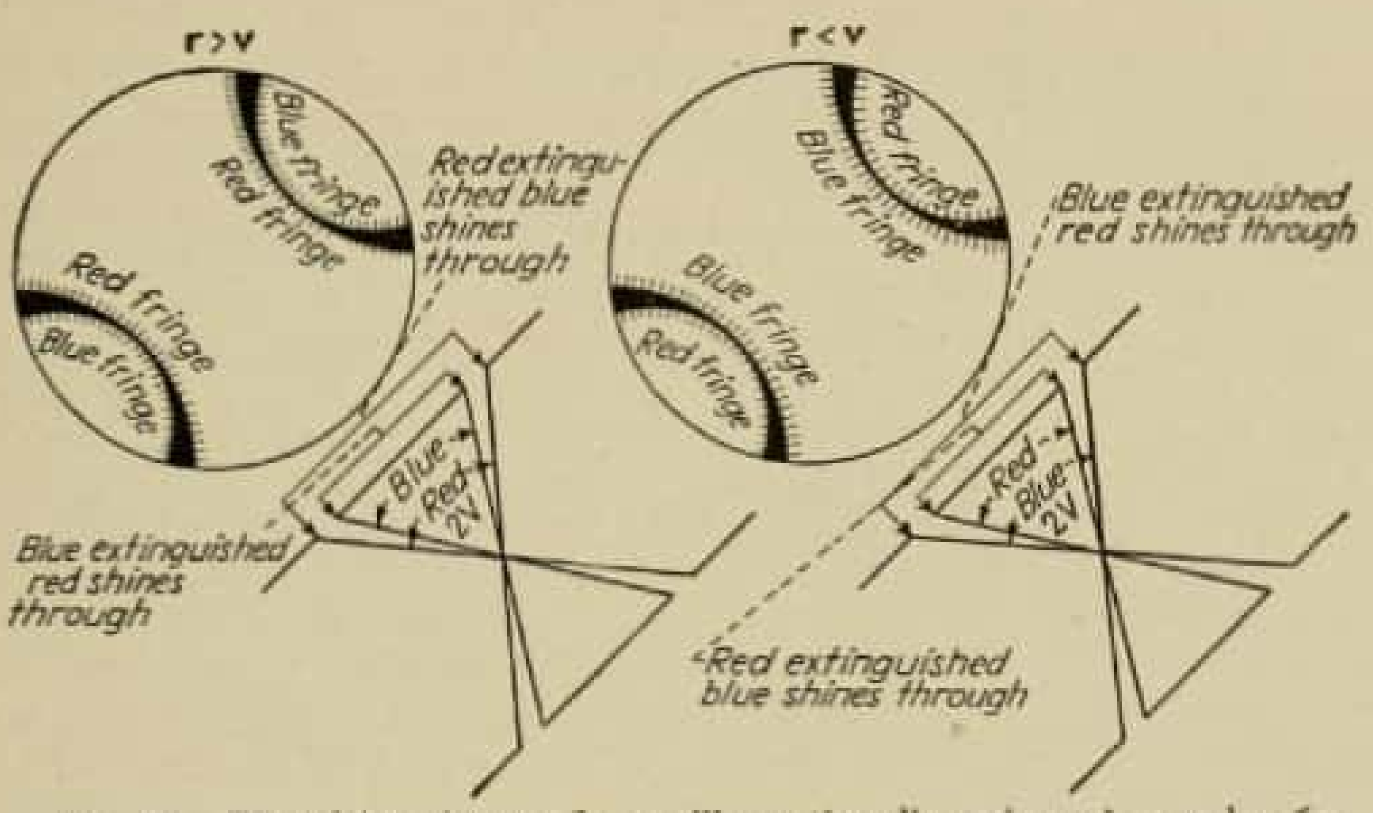


FIG. 95.—Biaxial interference figures illustrating dispersion $r > v$ and $r < v$. The colored fringes as observed in the interference figure are reversed from the axial angles existing in the crystal due to extinction.

conclusion. On the concave side of the isogyre, as illustrated in the figure, red light is extinguished, and consequently the concave fringe is blue in color. Blue is extinguished on the convex side, and the fringe is red.

It should be emphasized that the symmetry of the interference figure is always governed by the symmetry of the mineral. Dispersion varies according to the symmetry of the crystal system. The various types, arranged according to crystal system, are as follows:

Orthorhombic crystals:
- Dispersion of the optic axes.
- Crossed axial plane dispersion.

Monoclinic crystals:
- Inclined dispersion (both bisectrices).
- Horizontal dispersion (acute bisectrix).
- Crossed dispersion (obtuse bisectrix).

Triclinic crystals:
- Unsymmetrical dispersion.

These types are best distinguished by the use of light of various wave lengths. Red and blue color filters to be placed in front of the mirror of the microscope are convenient.

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